S. HRG. 102-162

RENEWABLE HYDROGEN ENERGY RESEARCH AND DEVELOPMENT ACT OF 1991

HEARING

BEFORE THE

SUBCOMMITTEE ON
ENERGY RESEARCH AND DEVELOPMENT

OF THE

COMMITTEE ON
ENERGY AND NATURAL RESOURCES
UNITED STATES SENATE

ONE HUNDRED SECOND CONGRESS

FIRST SESSION

ON

S. 1269

TO REQUIRE THE SECRETARY OF ENERGY TO EXPEDITE THE DEVELOPMENT OF HYDROGEN DERIVED FROM RENEWABLE ENERGY SOURCES AS AN ALTERNATIVE ENERGY SYSTEM FOR RESIDENTIAL, INDUSTRIAL, UTILITY, AND MOTOR VEHICLE USE, AND FOR OTHER PURPOSES

JUNE 25, 1991

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RENEWABLE HYDROGEN ENERGY RESEARCH AND DEVELOPMENT ACT OF 1991

TUESDAY, JUNE 25, 1991

U.S. SENATE,
SUBCOMMITTEE ON ENERGY RESEARCH AND DEVELOPMENT,
COMMITTEE ON ENERGY AND NATURAL RESOURCES,
Washington, DC.

The subcommittee met, pursuant to notice, at 9:30 a.m., in room SD-366, Dirksen Senate Office Building, Hon. Wendell H. Ford, presiding.

OPENING STATEMENT OF HON. WENDELL H. FORD, U.S. SENATOR FROM KENTUCKY

Senator FORD. Good morning, ladies and gentlemen.

Today we will receive testimony on S. 1269, the "Renewable Hydrogen Energy and Development Act of 1991." The bill would direct the Secretary of Energy to speed up the development of hydrogen for use in our homes, businesses, and cars. This bill was introduced by our distinguished colleague from Iowa, Senator Harkin.

Hydrogen is an attractive fuel because it can be produced from water. In addition, there is little environmental impact from the burning of hydrogen. But there is still more work needed to make hydrogen economical and efficient.

This subcommittee has overseen and encouraged the Department's work on hydrogen for many years. Senator Matsunaga, who used to be a member of this committee, pushed hard to pass legislation in this area. Senator Matsunaga's bill was enacted into law last year. It established a hydrogen research and development program at the Department of Energy to find the answers to some of the remaining questions about hydrogen. The Department is now implementing that law.

I look forward to the hearing this morning and to listen to the witnesses on the Department's hydrogen efforts and on the need for this legislation.

[A prepared statement from Senator Wallop and the text of S. 1269 follow:]

PREPARED STATEMENT OF HON. MALCOLM WALLOP, U.S. SENATOR FROM WYOMING

Good morning, ladies and gentlemen. In our search for alternative energy sources, hydrogen often is cited as an abundant and environmentally benign fuel. As long ago as May 1961 an issue of *Fortune* magazine cited hydrogen as by far the most abundant, energetic, and cleanest of all the elemental fuels in the universe, predicting that it "may well be the decisive technology of this century."

Subsequently, in November 1972, *Fortune* predicted that "we may well be using [hydrogen] within the decade. . . . On great floating platforms in the oceans, some number of miles offshore, a series of big nuclear power plants would be built. . . . From the inexhaustible seas, hydrogen would flow continuously onshore . . ."

Once again the technology soothsayers were overly optimistic, to say the least; but this was not the first, nor will it be the last, time.

This observation is not meant to demean the importance of hydrogen in our future energy strategy. Since enactment of the Federal Non-nuclear Research and Development Act of 1974, this Committee has supported research on a broad spectrum of energy technologies, including hydrogen, fuel cells and other technologies with applications in transportation.

Building on this history, during the last Congress major initiatives were enacted in the Spark M. Matsunaga Hydrogen Research, Development and Demonstration Act of 1990. Even now the Hydrogen Technical Advisory Panel is being formulated to assists in establishment of a five year program management plan.

Complementing this effort, the Renewable Energy and Energy Technology Competitiveness Act of 1989 calls for the establishment of 1995 goals for DOE's hydrogen energy system program. If the requested funds are appropriated for these programs, the Department intends to implement these programs in fiscal year 1992.

Additional initiatives are included in S. 1220, the National Energy Security Act of 1991, which is awaiting Senate action. In the formulation of S. 1220 considerable attention was given to the future energy requirements of the United States for transportation. Major research and development initiatives were included such as high-efficiency heat engines and hybrid-electric and electric vehicles.

These initiatives also include new engine technologies that rely on alternative fuels both as primary fuels such as natural gas and as energy storage fuels, such as hydrogen. In addition, S. 1220 authorizes field demonstration of hybrid-electric vehicles and the necessary infrastructure to support their deployment throughout urban areas.

National energy and transportation policies are intertwined. Our country's economic vitality is dependent on the efficient transportation of people, goods and services. In the future, hydrogen and fuel cells offer considerable potential.

The intent of S. 1269 is to expedite the development of hydrogen from renewable energy sources and its use as an alternative energy source. Like existing law, it would appear to require DOE to formulate comprehensive hydrogen program plan. Similarly, like existing law and additional authorities contained in S. 1220, additional joint ventures are authorized by S. 1269.

I am therefore interested in knowing if S. 1269 complements recent and pending Congressional actions to foster advance DOE's program activities on hydrogen production and use, or if it is simply redundant.

II

102D CONGRESS
1ST SESSION

S. 1269

To require the Secretary of Energy to expedite the development of hydrogen derived from renewable energy sources as an alternative energy system for residential, industrial, utility, and motor vehicle use, and for other purposes.

IN THE SENATE OF THE UNITED STATES

JUNE 11, 1991

Mr. HARKIN introduced the following bill; which was read twice and referred to the Committee on Energy and Natural Resources

---

A BILL

To require the Secretary of Energy to expedite the development of hydrogen derived from renewable energy sources as an alternative energy system for residential, industrial, utility, and motor vehicle use, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE.

This Act may be cited as the "Renewable Hydrogen Energy Research and Development Act of 1991".

SEC. 2. FINDINGS.

Congress finds that—

(1) alternative fuels to replace or augment fossil fuels must be developed;

(2) hydrogen is the most plentiful element in the universe;

(3) hydrogen is a promising alternative fuel that can be manufactured from a variety of energy sources, including renewable energy sources such as solar thermal, photovoltaics, wind, biomass, hydroelectric, and geothermal;

(4) hydrogen can serve as an effective storage medium for intermittent energy sources such as solar and wind;

(5) hydrogen is the fuel for the Space Shuttle main engines and provides electricity and water for the astronauts by way of clean-burning fuel cells;

(6)(A) the use of hydrogen has been demonstrated in commercial aircraft; and

(B) hydrogen is the only fuel suitable for hypersonic aircraft;

(7) hydrogen is an environmentally attractive, carbon-free fuel that produces—

(A) no global warming greenhouse gases;

(B) no acid rain;

(C) no ozone precursors that generate urban smog;

(D) no stratospheric ozone depleting chemicals;

(E) no radioactive waste;

(F) no toxic air pollution; and

(G) if used in a fuel cell to produce electricity, negligible nitrous oxides;

(8) hydrogen can meet the requirements for zero emission vehicles;

(9) when the hydrogen is produced from a renewable energy source, a system of electric vehicles powered by hydrogen by way of fuel cells produces no environmentally significant greenhouse gas or air pollution emissions of any kind, in either fuel production or use, and is therefore a zero emission transportation system;

(10) hydrogen, when added to conventional hydrocarbon fuels, reduces emissions from the combustion process;

(11) hydrogen has been studied for use in rail locomotives, particularly for transport of liquid hydrogen;

(12) the practical use of hydrogen as a vehicle fuel can build logically on prior experience with natural gas and electric vehicles; and

(13) current hydrogen production and combustion technologies can be useful components of a transition strategy that would lead to future zero-emission hydrogen production and end-use systems.

SEC. 3. PURPOSES.

The purposes of this Act are to—

(1) reduce the United States' dependence on imported oil;

(2) accelerate the development of renewable hydrogen as an alternative energy source to fuel homes, factories, utilities, and motor vehicles;

(3) plan for and accelerate research and development programs on components of a renewable hydrogen energy system;

(4) reduce emissions of—

(A) greenhouse gases;

(B) acid rain;

(C) precursors to urban smog; and

(D) other air pollution; and

(5) establish industry and government cost shared projects to speed the development of renewable hydrogen energy systems.

SEC. 4. DEFINITIONS.

As used in this Act:

(1) GREENHOUSE GAS.—The term "greenhouse gas" means a gas that, when released into the atmosphere, contributes to global warming by trapping infrared radiation.

(2) RENEWABLE ENERGY SOURCE.—The term "renewable energy source" means a source of energy (such as solar thermal, photovoltaics, wind, hydroelectric, and geothermal) that is not depleted by continued use.

(3) SECRETARY.—The term "Secretary" means the Secretary of Energy.

(4) ZERO EMISSION.—The term "zero emission" means resulting in the emission of no environmentally significant quantities of—

(A) greenhouse gases (primarily carbon dioxide and methane);

(B) carbon monoxide;

(C) precursors to acid rain or smog;

(D) nitrous oxides;

(E) formaldehyde; or

(F) other toxic air pollutants.

SEC. 5. RENEWABLE HYDROGEN ENERGY SYSTEM RESEARCH AND DEVELOPMENT.

(a) RESEARCH AND DEVELOPMENT PROGRAMS.—Not later than 18 months after the date of the enactment

of this Act, the Secretary shall, in accordance with the Federal Nonnuclear Energy Research and Development Act of 1974 (42 U.S.C. 5901), solicit proposals and award contracts to conduct—

(1) at least one program to develop, build, and test a system for generating hydrogen from renewable energy sources;

(2) at least one program to develop, build and test catalytic hydrogen gas diffusion burners for residential furnaces and stoves to permit low temperature, high efficiency combustion of hydrogen without the need for exhaust fans or chimneys, with a goal of greater than 95 percent combustion efficiency;

(3) at least one program to evaluate the ability of existing natural gas pipelines to carry hydrogen gas, including experimentation if needed, with a goal of determining those components of the natural gas distribution system that would have to be modified to carry (A) more than 20 percent hydrogen mixed with natural gas and; (B) pure hydrogen gas;

(4) at least one program to develop, build, and test at least one hydrogen storage system suitable for electric vehicles powered by way of fuel cells, with emphasis on—

(A) improved metal hydride hydrogen storage;

(B) activated carbon-based hydrogen storage;

(C) high pressure compressed hydrogen; or

(D) other novel hydrogen storage techniques;

(5) at least one program to design, build, and test a fuel cell suitable to power an electric motor vehicle; and

(6) such other research and development programs as are considered necessary by the Secretary to carry out this Act.

(b) PLAN.—

(1) IN GENERAL.—The Secretary, in consultation with the Hydrogen Technical Advisory Panel established by section 108 of the Spark M. Matsunaga Hydrogen Research, Development, and Demonstration Act of 1990 (42 U.S.C. 12407), the Secretary of Transportation, the Administrator of the Environmental Protection Agency, and other State and local public and private organizations that the Secretary considers appropriate, shall prepare a comprehensive multi-year research and development plan to facili-

tate the development of renewable hydrogen energy systems at the earliest feasible date.

(2) COMPONENTS OF PLAN.—The plan shall include—

(A) an evaluation of the critical technologies required to implement a hydrogen energy system, including—

(i) renewable hydrogen generation, including electrolyzers designed to operate with renewable energy sources;

(ii) hydrogen fixed storage and transmission;

(iii) hydrogen on-board mobile storage and refueling;

(iv) fuel cells;

(v) hydrogen catalytic combustion burners; and

(vi) electric vehicles powered by fuel cells;

(B) a review of hydrogen research and development programs established by foreign countries;

(C) projections of the manufacturing costs over the next 30 years of all elements of renewable hydrogen energy systems, including—

(i) systems to generate hydrogen from renewable energy sources;

(ii) systems to store hydrogen for residential, industrial, utility, and transportation purposes;

(iii) systems, such as catalytic combustion burners, to burn hydrogen efficiently;

(iv) fuel cells for stationary and mobile applications;

(v) passenger vehicles with similar acceleration and ranges as vehicles with gasoline powered internal combustion engines; and

(vi) passenger vehicles with lesser ranges than vehicles with gasoline powered internal combustion engines, but suitable for commuting to and from places of employment within typical metropolitan areas;

(D) projections of the costs of producing hydrogen over the next 30 years from renewable energy sources, as compared to the projected costs of petroleum-based fuels and other alternative fuels;

(E) projected life-cycle costs of owning and operating electric vehicles powered by hydrogen by way of fuel cells over the next 30 years, as compared to life-cycle costs of owning and operating—

(i) vehicles with gasoline powered internal combustion engines; and

(ii) electric vehicles powered by storage batteries;

(F) the necessary technical milestones and cost objectives for critical technologies such that renewable hydrogen energy systems become cost competitive with fossil fuels within the next 10 through 20 years for applications including—

(i) residential use, including catalytic combustion burners;

(ii) commercial co-generation of electricity and heating by way of fuel cells;

(iii) industrial use;

(iv) utility load-leveling; and

(v) motor vehicle use including passenger cars, trucks, buses, and rail locomotives;

(G) a plan for and prioritization of research activities to attain the milestones and

cost objectives established in subparagraph (F), including an estimate of the research costs and schedule necessary to achieve the milestones and cost objectives, with emphasis on government and industry cost-sharing joint ventures to accomplish major tasks; and

(H) a plan and cost estimate for producing a quantity of electric vehicles powered by hydrogen by way of fuel cells, and renewable hydrogen production equipment, sufficient to permit the evaluation of a renewable hydrogen transportation system with zero emissions in at least one centrally fueled fleet application.

(3) SUBMISSION OF PLAN.—Not later than 1 year after the date of enactment of this Act, the Secretary shall submit the final plan to the—

(A) Committee on Energy and Natural Resources of the Senate; and

(B) Committee on Science, Space, and Technology of the House of Representatives.

(c) AUTHORIZATION OF APPROPRIATIONS.—There are authorized to be appropriated to the Secretary such sums as are necessary to carry out this section.

SEC. 6. RENEWABLE HYDROGEN ENERGY SYSTEM JOINT VENTURE DEMONSTRATION PROJECTS.

Section 6 of the Renewable Energy and Energy Efficiency Technology Competitiveness Act of 1989 (42 U.S.C. 12005) is amended—

(1) in subsection (b), by striking paragraph (4) and inserting the following new paragraph:

"(4) DRAFT SOLICITATIONS AND PUBLIC COMMENT.—The Secretary shall issue a draft solicitation for joint ventures under paragraphs (1) through (5) of subsection (c) by September 30, 1990, and draft solicitations for joint ventures under paragraphs (6) through (8) of subsection (c) by September 30, 1992. After issuing a draft solicitation, the Secretary shall, before issuing a final solicitation, provide for a period of public comment of not to exceed 60 days."; and

(2) in subsection (c), by adding at the end the following new paragraphs:

"(6) RENEWABLE HYDROGEN ENERGY PRODUCTION.—(A) The Secretary shall solicit proposals for and provide financial assistance to at least two joint ventures for the demonstration of the production of hydrogen using renewable energy sources.

"(B) The purpose of joint ventures supported under this paragraph shall be to design, build, test,

and demonstrate the production of hydrogen using renewable energy sources. The joint ventures shall operate the hydrogen production system and collect sufficient data to allow estimation of hydrogen production costs and system reliability.

"(C) There are authorized to be appropriated to the Secretary such sums as are necessary to carry out this paragraph.

"(D) As used in this paragraph, the term 'renewable energy source' means a source of energy (such as solar thermal, photovoltaics, wind, biomass, hydroelectric, and geothermal) that is not depleted by continued use.

"(7) UTILITY LOAD-LEVELING SYSTEM.—(A) The Secretary shall solicit proposals for and provide financial assistance to at least one joint venture for the demonstration of an electric utility load-leveling system with hydrogen as the storage medium.

"(B) The purpose of joint ventures supported under this paragraph shall be to design, build, test, and demonstrate an electric utility load-leveling system that produces hydrogen during off-peak hours, and consumes that hydrogen in a fuel cell during the hours of maximum utility electricity demand, in order to cut the peak power level required from the

utility by at least 10 kilowatts. The joint venture shall operate the system and collect sufficient data to predict the costs, efficiency, and reliability of the systems.

"(C) There are authorized to be appropriated to the Secretary such sums as are necessary to carry out this paragraph.

"(8) RENEWABLE HYDROGEN TRANSPORTATION SYSTEM.—(A) The Secretary shall solicit proposals for and provide financial assistance to at least two joint ventures for the demonstration of a renewable hydrogen zero emission transportation system in accordance with this paragraph.

"(B) The purpose of joint ventures supported under this paragraph shall be to design, build, test and demonstrate the operation of at least four prototype electric vehicles powered by hydrogen by way of fuel cells, with the hydrogen derived from a renewable energy source. The vehicles shall be suitable for commuting use within metropolitan ozone nonattainment areas (as designated pursuant to section 107(d) of the Clean Air Act (42 U.S.C. 7407(d))), or for other centrally fueled fleet operations within the areas.

"(C) There are authorized to be appropriated to the Secretary such sums as are necessary to carry out this paragraph.

"(D) As used in this paragraph:

"(i) The term 'greenhouse gas' means a gas that, when released into the atmosphere, contributes to global warming by trapping infrared radiation.

"(ii) The term 'renewable energy source' means a source of energy (such as solar thermal, photovoltaics, wind, biomass, hydroelectric, and geothermal) that is not depleted by continued use.

"(iii) The term 'zero emission transportation system' means a system that results in the emission of, either during normal production of the fuel or in operation of the transportation system, no environmentally significant quantities of—

"(I) greenhouse gases (primarily carbon dioxide and methane);

"(II) carbon monoxide;

"(III) precursors to acid rain or smog;

"(IV) nitrous oxides;

"(V) formaldehyde; or

"(VI) other toxic air pollutants.".

Senator FORD. Let me just say to all of you this morning that at 11:30 this hearing will be over, whether we are through or not, because votes will start at that time and continue till about 12:30, and then they will start voting shortly after that at about 2:30. So, for all practical purposes, we must finish by 11:30. So, with those circumstances, I ask all the witnesses this morning to highlight their testimony, with the exception of my distinguished colleague, Senator Harkin, so that some questions and statements may be put in the record in order to accomplish this.

With that little comment, Senator Harkin, we are pleased that you are here this morning and look forward to your testimony.

STATEMENT OF HON. TOM HARKIN, U.S. SENATOR FROM IOWA

Senator HARKIN. Mr. Chairman, thank you very much, and thank you for holding this hearing on S. 1269. I am appreciative of the time constraints on you, not only as a Senator, but as your position as the Majority Whip and the duties that you have to fulfill on the floor of the Senate. So I am most appreciative of the time that you would give to have this hearing on my bill, not only to hear me, but to hear some distinguished individuals, who are much more knowledgeable about the specifics of hydrogen generation and what it can be used for than I am.

I do not pretend to be a scientist. I am not. But you will have people here who are and who can really answer any technical or involved questions that you might have.

Let me just say, Mr. Chairman, that given the choice, an ideal energy source would encompass the following. It would be renewable, economically viable, produced exclusively within the United States, and have no significant impact on the environment. Renewable energy sources, such as solar, thermal, photovoltaics, wind, biomass, and hydroelectric meet these requirements. And these renewable resources, primarily hydroelectric, do supply almost 5 percent of our supply today in the United States.

The problem with solar energy, as we know, is it is intermittent. It is all right when the sun is shining. You can make electricity or whatever, but at nighttime it is not any good. So we have to figure out some way of taking that energy and storing it and transmitting it later on. And I contend that hydrogen is one of those ways.

You remember, Mr. Chairman, when you were in chemistry class in high school, one of the first experiments we did was we stuck two electrodes in the water and out came hydrogen on one and oxygen came up on the other one when you put an electric current through it.

Senator FORD. That is what the coach did to us when we were not playing very well.

[Laughter.]

Senator HARKIN. That is right. That is true. There were a lot of things we used to do like that.

And that is basically as simple as it is, right there. And you can obviously use solar energy for either photovoltaics or whatever it might be, wind, biomass, or whatever, to generate the electricity needed to do that. I might also add an area of interest of yours, Mr.

Chairman, coal gasification being used to get the hydrogen out of the coal to do the same thing, to make that hydrogen.

So it really is an ideal source. A lot of towns before World War II, I know in Iowa, and imagine maybe in Kentucky, burned what we called town gas, which really was a mixture of hydrogen gas. They did not know it at the time, but that is exactly what it was. It was a mixture of hydrogen, carbon monoxide, and some other things that they burned as town gas in a lot of towns in Iowa and other places.

Hydrogen can generate electricity with no moving parts in a fuel cell. We have seen that in the space program. It will continue to produce electricity as long as it is supplied with hydrogen and oxygen, using no moving parts. So we already have the capability of doing that. And as I said, it is an ideal environmental fuel. You burn it and all you get is pure, clean water. There is no acid rain, no global warming, and no depleting chemicals of ozone and carbon monoxide. And no radioactive waste.

As to the cost, Joan Ogden of the Princeton Center for Energy and Environmental Studies will testify later on, on some of the cost aspects of what we are looking at here with hydrogen.

But, in essence, Mr. Chairman, all I wanted to bring to your attention this morning was that in DOE this is virtually being ignored as a potential resource. The total funding is $2.6 million for next year. They also requested about $9.5 million for the development of fuel cells. DOE's total budget is $18.6 billion. Even if we subtracted the $11.8 billion for nuclear weapons research, the administration has $6.8 billion left for all civilian energy programs.

I contend that $2.6 million of $6.8 billion, or less than 0.04 percent, is totally inadequate for one of the most promising energy sources for the 21st century. Some comparisons, Mr. Chairman: DOE requests almost $400 million for nuclear fission R&D and $337 million for nuclear fusion R&D. I might just stop right there.

Also, Mr. Chairman, they say, well, you are going to hear from DOE saying they do not support it because this is too far in the future and that we are not there yet, but they are putting about $500 million a year into fusion. And I challenge anyone to show me that fusion is going to produce any kind of viable electricity for this country or anywhere else probably before the middle of the next century. So they are pumping $500 million a year into that, and yet about $2 million or so into hydrogen.

So I would like to compare that in terms of the future; $534 million for the Superconducting Super Collider, et cetera, et cetera. So I am just saying, Mr. Chairman, that for one of the most promising energy sources, one that we know how to develop, we are using it in fuel cells, and in fact in some areas you will hear testimony that it is already economically viable, they are putting very little research into it.

The Province of British Columbia, and you will be hearing from someone who can speak about that, is planning to spend about $20 million a year on hydrogen energy research. Keith Prater, representing a company from British Columbia, will be testifying on this.

British Columbia, Mr. Chairman, has 1 percent of our population, and they are spending $20 million on hydrogen energy re-

search, and we are only spending $2.6 million. So my bill, basically, would establish five specific renewable hydrogen R&D projects and three cost shared, Government with industry, demonstration projects. I have met with people from the industry. They are ready to move on this. They are ready to cost share on those items that are in this bill.

So again, Mr. Chairman, thank you for having this hearing. The more I have become knowledgeable about hydrogen and the possibilities of hydrogen, how we can make it, how it can be transmitted through natural gas pipelines right now that are existing all over this country, how we can burn it in fuel cells, and how some companies right now are manufacturing fuel cells that are economically competitive right now, I guess for peak saving, and to think about all of the wasted solar energy that is hitting the earth and that we are now using to make something that can be stored and transmitted for later use, like hydrogen.

Again, I am not saying that it is a panacea, I am not saying that it is something that we can have tomorrow or next year or 4 years from now, but I believe it is something that if we put at least a modest amount of research and development money into, that within our lifetimes we could see some appreciable use of hydrogen as a clean, renewable energy source in this country.

Thank you very much, Mr. Chairman.

[The prepared statement of Senator Harkin follows:]

PREPARED STATEMENT OF HON. TOM HARKIN, U.S. SENATOR FROM IOWA

Mr. Chairman, I appreciate your calling this hearing on my bill, S. 1269, the Renewable Hydrogen Energy Research and Development Act of 1991, and I appreciate the opportunity to testify before your committee this morning. In my judgment, the use of hydrogen as an energy carrier derived from renewable energy sources is one of the most promising alternatives to fossil fuels to reduce our dependence on imported oil while protecting the environment.

I wrote this bill to accelerate the development of a long-term supply of energy that meets three basic criteria: the ideal energy source should be:

- renewable,
- produced exclusively within the United States, and
- have no significant impact on the environment.

Renewable energy sources such as solar thermal, photovoltaics, wind, biomass and hydroelectric meet these criteria, but some of these solar energy sources are intermittent or unsuitable for use in the transportation sector.

These limitations of renewable energy can be eliminated by combining solar energy with hydrogen as the storage medium and energy carrier. The solar energy is used to electrolyze water, forming oxygen and hydrogen gas. The hydrogen can then be stored for later use in homes, factories and motor vehicles.

Hydrogen can be burned in furnaces and stoves, substituting for natural gas. Before World War II, many homes in America burned "town gas," a mixture of hydrogen and carbon monoxide.

Hydrogen can generate electricity directly with no moving parts in a fuel cell, a device similar to a battery. Unlike a battery, however, a fuel cell continues to produce electricity as long as it is supplied with hydrogen and oxygen (or air). Our astronauts on the Space Shuttle derive electricity and water from fuel cells powered by hydrogen and oxygen.

Hydrogen is the ideal environmental fuel. Burning hydrogen in oxygen produces pure, clean water. No acid rain, no global warming greenhouse gases, no stratospheric ozone depleting chemicals, no carbon monoxide, no urban smog and no radioactive waste.

Hydrogen burned in air does produce some nitrous oxides, but even this pollution can be reduced to negligible levels with a low temperature catalytic burner, and fuel cells produce no environmentally significant quantities of nitrous oxide, or any other air pollution.

The main roadblock to utilizing renewable hydrogen is cost: the cost to produce hydrogen from renewable energy, and the cost to develop the infrastructure to store, transport and burn hydrogen.

However, projections show that renewable hydrogen energy could become competitive with fossil fuels with sufficient development. Joan Ogden of Princeton's Center for Energy and Environmental Studies will testify later on her research on the future costs of hydrogen produced from various forms of solar energy.

The Department of Energy in its report of March, 1990, "The Potential of Renewable Energy: an Interlaboratory White Paper," concluded that hydrogen produced from photovoltaics would cost the equivalent of about $4.30 per gallon of gasoline, but that this cost could fall to $1.40 per gallon equivalent by the year 2030.

While this may seem expensive, keep in mind that we already pay the equivalent of $2.70 per gallon of gasoline for residential electricity, a very clean (at least for the end-user) and versatile energy source. That is, residential electricity at 8 cents per kilowatt hour, the average U.S. price, is equivalent in energy terms to $2.70 per gallon of gasoline. Electricity sells for up to $3.60 per gallon of gasoline equivalent in the northeastern U.S. today.

Consumers are willing to pay this premium for the convenience of electricity. I contend that citizens may gladly pay as much for clean burning hydrogen made from renewable, indigenous energy sources, particularly if renewable hydrogen reduces acid rain, urban smog, the potential for global warming, and our dependence on foreign oil.

Despite the great promise of renewable hydrogen, the Department of Energy has virtually ignored this potential resource. Total funding for hydrogen energy research is $2.6 million in the administration's request for fiscal year 1992. The DOE has also requested $9.5 million for development of fuel cells, a primary component of many hydrogen energy systems.

But consider the total DOE budget: $18.6 billion. Even if we subtract the $11.8 billion for nuclear weapons research, the administration has $6.8 billion left for all civilian energy programs. I contend that $2.6 million out of $6.8 billion, or less than 0.04 percent is totally inadequate for one of the most promising energy sources for the 21st century.

Mr. Chairman, the DOE has requested almost $400 million for nuclear fission R&D, $337 million for nuclear fusion R&D, $534 million for the Super Conducting Super Collider, $227 for fossil fuel R&D, and $715 million for basic energy research. Shouldn't we consider diverting at least $20 to $30 million each year from techniques to accelerate production of fossil fuel and nuclear energy to renewable hydrogen?

Other nations are pursuing the hydrogen path with much more vigor. Germany and Saudi Arabia have worked together since 1986, building three facilities to produce solar hydrogen, including projects such as catalytic burners and fuel cells to efficiently utilize hydrogen. The province of British Columbia is planning to spend $20 million per year on hydrogen energy research. Keith Prater, representing a company from British Columbia will be testifying here this morning. I understand the Canada's green plan may also include hydrogen energy research on a scale similar to the British Columbia effort.

Mr. Chairman, if British Columbia, with only one percent of the population of the United States can spend $20 million per year on hydrogen energy research and development, shouldn't we be able to spend more than $2.6 million?

The bill I have introduced, S. 1269, would build on the landmark Matsunaga bill passed by Congress last year. The Matsunaga bill (42 U.S.C. 12407), requires the Department of Energy to set up a Hydrogen Technical Advisory Panel and to develop a five-year hydrogen management plan. It also urges (but does not require) the Secretary of Energy to give "priority" to producing hydrogen from renewable energy sources, and permits (but does not require) the DOE to conduct research on hydrogen. Unfortunately, the money authorized for this effort ($3 million for FY 1992) is not adequate.

My bill would establish five specific renewable hydrogen R&D projects and three cost-shared government/industry demonstration projects. The bill also requires DOE to prepare a plan specifically for the development of renewable hydrogen, including projections of life cycle costs of a zero emission transportation system based on electric vehicles driven by fuel cells powered by renewable hydrogen.

The five R&D projects in my bill would:

- investigate hydrogen production from renewable energy sources;
- develop low temperature catalytic burners for residential use in stoves and space heaters;

- evaluate the ability of natural gas pipelines to carry hydrogen or mixtures of hydrogen and methane;
- develop hydrogen storage systems for use on motor vehicles; and
- develop fuel cells for electric vehicles.

In addition, my bill would establish three categories of government/industry cost shared demonstration projects to move hydrogen technology out of the laboratory and into the real world, giving industry "hands-on" experience integrating hydrogen technology into practical uses including:

- at least two joint ventures to produce hydrogen from renewable energy sources;
- at least one joint venture to demonstrate utility load leveling, whereby hydrogen gas is generated at night, during off-peak hours, and that hydrogen is then burned during the afternoon utility peak hours to avoid the costs of extra base-load capacity; and
- at least two joint venture projects to design, build and test at least four electric vehicles powered by hydrogen via fuel cells.

These programs would form the basis of a vigorous R&D and demonstration program, knitting together the elements needed to demonstrate the potential of a renewable hydrogen energy system.

Mr. Chairman, I have no allusions about renewable hydrogen displacing all fossil fuels or all nuclear power in the foreseeable future. We will have to look toward a mixture of energy sources as we enter the 21st century. But I do believe that to ignore the only energy source that offers the promise of a totally renewable, sustainable energy supply with no adverse environmental impact of any kind, and with no foreign dependence, would be a grave disservice to our children and grandchildren.

I thank you for holding this hearing, and look forward to your support for this program.

Senator FORD. Thank you very much, Senator.

It is my understanding—and I do not have any questions for you—that there is about $30 million worth of research being done by the military in the field of hydrogen.

Senator HARKIN. $30 million?

Senator FORD. Yes.

And there may be some way for us to dovetail—my figure may be a little bit one way or the other, but it is in the ball park I think. But it is basically for military and not in the non-military field, so we might be able to find a way to dovetail those two. I am not sure we can.

Senator HARKIN. That would be all right. I was not aware of that.

Senator FORD. There are more ways to skin a cat around here than we might realize.

Senator HARKIN. You bet.

Senator FORD. So, we look forward to the other witnesses, and thank you for your interest in this piece of legislation, and I assure you we will move forward with it.

Senator HARKIN. Thank you. And again, Mr. Chairman, I really appreciate your time on this. I really know how busy you are, being WHIP and everything, and I just really appreciate your taking the time.

Senator FORD. Well, when I am here I am not having to do something else, too.

Senator HARKIN. Thank you, Mr. Chairman.

Senator FORD. Thank you, Tom.

The next witness will be Dr. Robert L. San Martin, Deputy Assistant Secretary for Utility Technologies in the Department of Energy.

Doctor, we are delighted to see you this morning, and hopefully you can highlight your statement, which we have now for the record, and we may move on with a few questions.

And I might say to all of our witnesses this morning that there may be some additional questions that will be submitted to all of the witnesses in writing, and ask that they respond in a timely manner.

Doctor, you may proceed.

STATEMENT OF DR. ROBERT L. SAN MARTIN, DEPUTY ASSISTANT SECRETARY FOR UTILITY TECHNOLOGIES, DEPARTMENT OF ENERGY

Dr. SAN MARTIN. Thank you, Mr. Chairman. I will be very happy to summarize my statement. The Department and I thank you for the opportunity to appear before the committee and discuss our hydrogen energy research programs and our advanced fuel cell programs, and also provide comments on S. 1269, the Renewable Hydrogen Energy Research and Development Act of 1991.

The Department of Energy has been conducting research and development to produce, store, and utilize hydrogen since the 1970's. This research has been primarily supported by the Office of Conservation and Renewable Energy, even though several other offices within the Department have also participated in the overall hydrogen program.

As stated by Senator Harkin within his own bill, hydrogen is not a primary energy source. It must be produced from water or other compounds by consuming energy in amounts which are significantly greater than that represented by the resultant energy in the hydrogen that is produced. In this way, hydrogen is an energy carrier analogous to electricity.

Major sources of hydrogen today of course come from primarily natural gas, even though light oils, coal, and water are also used for production of hydrogen today. In the near term, production of hydrogen is certainly going to be limited by the availability of lower-cost competing fuels and the high energy requirements of the most current hydrogen-producing technologies.

Today, the only economically used nonfossil fuel process for hydrogen production is electrolysis of water. Electrolysis requires expensive electric power input, and therefore is used only when the cost of hydrogen has a minor impact on the intended application. Our program goal is to produce hydrogen from renewable energy resources for less than $10 per million Btu. At this cost, electricity could be generated for 10 to 15 cents per kilowatt hour, and a fuel cell vehicle could be operated at a cost that is comparable to gasoline, at about $1.25 per gallon.

The research programs which we have pursued on hydrogen production from nonrenewable resources include photoconversion processes, which are less developed than the electrolysis processes, and offer a potential for the long term. We have also conducted a number of research activities dealing with the storage of the hydrogen resource itself.

We also conclude, Mr. Chairman, that fuel cells are an attractive way to convert hydrogen to electricity, since they produce power

electrochemically and are not constrained by the Carnot cycle limits of heat engine conversion efficiencies. This theoretical limit is approximately twice that of conventional conversion technologies. DOE is pursuing a coordinated fuel cell technology development program that is applicable to all major energy end-use sectors. This research is supported by the Office of Conservation and Renewable Energy and also supported by the Office of Fossil Energy.

The Fossil Energy effort is directed towards larger utility and on-site systems, while we are focusing on transportation and other stand-alone applications, including several of those applications that are emphasized in this bill. Fossil Energy supports research in molten carbonate and solid oxide fuel cells, and has supported phosphoric acid fuel cells up to the point of commercial readiness. Our research has involved the development of phosphoric acid fuel cells for transportation, and we are in the process of demonstrating that particular technology on three different vehicles.

In addition, our research has also focused on the proton exchange membrane fuel cell. All hydrogen research is coordinated internally, with all elements involved in the Department exchanging results and future plans on a regular basis.

Let me now turn to specific comments on S. 1269. This bill would bypass, in our opinion, Mr. Chairman, the research needed to develop a potentially competitive technology and, instead, would go at too fast a rate to attempt to demonstrate hydrogen as a transportation fuel before it is technically and economically competitive. Consequently, the Department does not support the bill.

While hydrogen may be an attractive fuel in the long term, it is not now in the same category as methanol, ethanol, compressed or liquified natural gas, or electric power, due primarily to its high cost. We believe that a demonstration program is premature, given the state of conversion economics, storage technologies for on-board or service station use, and fuel cell technology suitable for road vehicles. We believe that funds in this area could be more effectively spent at this time on continuing the research and development process.

To summarize, Mr. Chairman, we believe that the goal of realizing the promise of hydrogen is a very good goal, and we do support that. But the Department believes that the aggressive implementation of this bill would showcase the limitations of hydrogen, rather than the potential of this technology. We also believe, Mr. Chairman, that the bill would restrict the Department of Energy's flexibility in managing the hydrogen research and fuel cell programs. And, in light of already ongoing R&D activities relating to hydrogen conversion, storage, and utilization, we believe that the requirements of this bill are premature at this time.

We thank you for the opportunity to discuss this issue with you today, and we would be happy to respond to any of your questions.

[The prepared statement of Dr. San Martin follows:]

PREPARED STATEMENT OF DR. ROBERT L. SAN MARTIN, DEPUTY ASSISTANT SECRETARY FOR UTILITY TECHNOLOGIES, DEPARTMENT OF ENERGY

Mr. Chairman and members of the Committee: Thank you for the opportunity to appear before you today to discuss the Department of Energy's hydrogen energy re-

search program and advanced fuel cell programs, and S. 1269, the Renewable Hydrogen Energy Research and Development Act of 1991.

Since the 1970s, the Department of Energy has conducted research and development to produce, store, and utilize hydrogen. The research is primarily supported by the Office of Conservation and Renewable Energy.

Hydrogen is not a primary energy resource. It must instead be produced from water or other compounds by consuming energy resources in amounts significantly greater than that represented by the resultant hydrogen product. In this way, hydrogen is an energy carrier, analogous to electricity. Hydrogen's long-term potential value lies primarily in serving as a nonpolluting energy pathway between certain primary energy resources and certain end-use applications.

Major sources of hydrogen today are natural gas, light oils, coal, and water. For the near-term hydrogen production will be limited by the availability of lower-cost competing fuels and the high energy requirements of most current production technologies. Today, the only commercially used nonfossil-fueled process for hydrogen production is electrolysis of water. Electrolysis requires relatively expensive electric power input and therefore is used where the cost of hydrogen has a minor impact on the intended application. One of our program goals is, therefore, to improve the efficiencies of existing hydrogen production processes or to devise new ones.

The program's cost goal is to produce hydrogen from renewable resources for less than $10 per million Btu. At this cost, electricity could be generated for 10 to 15 cents per kWh to meet peaking needs, and a fuel cell vehicle could be operated at a fuel cost comparable to gasoline at $1.25 per gallon.

Currently, the price of hydrogen is linked to the price of natural gas, since steam reforming of natural gas is the easiest and most efficient method of production. Based on an average price of natural gas of $3.80 per million Btu, hydrogen costs about $6.50 per million Btu. Projections for hydrogen produced from coal range from $7 to $15 per million Btu. In comparison, hydrogen produced by water electrolysis from grid electricity costs more than $20 per million Btu. Using present photovoltaic/electrolysis systems would result in hydrogen costs of $75 to $90 per million Btu. Thus, innovative or non-conventional production methods, such as solar-powered photoconversion technologies that do not involve the production of electricity, are needed to reduce costs and meet potential future hydrogen demands.

Photoconversion processes are less developed than electrolysis technologies, but offer potential for the long term. The single-step process of using solar energy directly to split water has the potential for increased efficiency and far lower system costs than electrolysis processes. However, photoconversion efficiencies are only a few percent at present. Research is under way on new materials to achieve greater efficiencies and reduce system costs, to improve cell design, and to develop a better understanding of electrode surfaces and the kinetics and mechanisms of oxygen and hydrogen evolution reactions.

Storage of hydrogen is still a problem, and more research is needed. Processes to store hydrogen as a cryogenic liquid consume one-third or more of the energy stored, and costs are estimated to be at least $8 per million Btu. More efficient liquefaction methods are being sought. Compressed gas storage is available but requires heavy, bulky cylinders; advances in materials and container design could bring needed improvements. Chemical storage methods include metal hydrides and activated carbons, but storage capacities have only reached 4 percent by weight, and additional improvements are needed. Research goals are aimed at improving the performance of activated carbon storage and developing new, less expensive hydride materials with greater storage capacity.

Fuel cells are able to convert the chemical energy in hydrogen and oxygen to electricity, creating water as a discharge product. Air can be used directly to supply the oxygen, and the hydrogen can be derived from a variety of energy sources, as previously described, or obtained as an industrial byproduct. Low-cost, high-performance fuel cells could help accelerate the introduction of cleaner fuels such as hydrogen and biofuels like methanol and ethanol.

Fuel cells are an attractive way to convert hydrogen to electricity, since they produce power electrochemically and are not constrained by the Carnot cycle limits of heat engine conversion efficiencies. The fuel cell's theoretical efficiency limit is about twice the theoretical limit for heat engines. Measured efficiencies of today's advanced fuel cells (50-55 percent) are already twice as high as those for today's internal combustion heat engine technology.

DOE is pursuing a coordinated fuel cell technology development program applicable in all major energy-use sectors. The research is supported by our office and the Office of Fossil Energy. The Fossil Energy effort is directed towards large utility systems, while we are focusing on transportation and other stand-alone applications,

including those emphasized in the bill under consideration. Fossil Energy supports research in molten carbonate and solid oxide fuel cells, and has supported phosphoric acid fuel cells up to the point of commercial readiness. Our research is focused on the proton exchange membrane (PEM) fuel cell. The approach is coordinated internally, with all involved elements of the Department exchanging results and future plans on a regular basis.

The type of fuel cell to be used for transportation applications is dictated in large part by size and weight limitations. The PEM fuel cell is relatively light and compact, and it operates at or near ambient temperature. In the last few years dramatic improvements in the performance of PEM fuel cells have been attained, due to the use of newly available experimental membranes and also due to improvements in catalyst technology. The new membranes allow the cell to operate at much higher current density, significantly improving the power density (one watt per square centimeter, or five times the previous value). Thus, for a given power rating, such as that required for a passenger car, less membrane is required and a smaller fuel cell can be used, thereby reducing power plant costs.

The second improvement is in catalyst technology. Through recent research and development, catalyst requirements for platinum in experimental cells have been reduced by a factor of 20 from those in current hardware. This reduction further lowers projected costs without a detrimental effect on performance.

Let me now turn to specific comments on S. 1269, the Renewable Hydrogen Transportation Development Act of 1991. This bill would bypass the research needed to develop a potentially competitive technology and instead would demonstrate hydrogen as a transportation fuel before it is technically and economically competitive; consequently, the Department opposes the bill. While hydrogen may be an attractive fuel in the long term, it is not now in the same category as methanol, ethanol, compressed or liquefied natural gas, or electric power due to its high cost. A demonstration program is premature given the state of conversion economics, storage technologies for on-board or service station use, and fuel cell technology suitable for road vehicles. The funds could more effectively be used for research.

We are concerned that a demonstration at this time will showcase the poor level of current technology and divert funds and attention from the research and technology development needed to enable hydrogen to serve in these applications. By mandating a series of specific activities, this bill would limit DOE flexibility in responding to technology developments and adjusting program priorities.

The 30-year cost and economic studies required by the bill would be primarily speculative at this time and would yield potentially misleading information. It is too early to predict the manner in which current efforts might result in commercially available technologies. The bill also presupposes that centrally manufactured hydrogen from renewable energy, carried on board and converted to electricity, will be the preferred energy pathway. Other nearer-term transitional pathways, such as liquid alcohol fuels from renewable resources powering a fuel cell, may have similar overall environmental signatures but present far fewer infrastructure problems.

The limitations of the PEM fuel cell technology have been high platinum content, expensive membranes, poor carbon monoxide tolerance, water management problems, and difficulty in thermal integration with a reformer. The DOE research program seeks to solve these problems.

To summarize, the Department's opposition to S. 1269 reflects three distinct concerns. First, the Department believes that it would showcase the limitations rather than the potential of new technology. Second, the bill would restrict DOE's flexibility in managing its hydrogen research and fuel cell programs. Third, in light of ongoing R&D activities relating to hydrogen conversion, storage, and utilization, the requirements of the bill would be largely premature.

Thank you for the opportunity to discuss these issues with you today.

Senator FORD. Thank you very much, Doctor. You did very well in bringing your statement into overview.

At last year's hearing, the Department testified that hydrogen would be a part of the administration's National Energy Strategy. How was hydrogen a part of the strategy?

Dr. SAN MARTIN. Mr. Chairman, as all of the alternatives were considered in the evolution of the National Energy Strategy in both the research section of the strategy and the alternative fuels strategy, reference is made in both of those to the need to continue the development of hydrogen, and pursue its eventual promise.

Senator FORD. The Renewable Energy Act of 1989 required the Department to recommend goals for hydrogen energy systems as part of its first annual report. Were those goals included in that report and, if so, what were they?

Dr. SAN MARTIN. Mr. Chairman, the Department, to the best of my knowledge, has not yet submitted the first annual report dealing with that particular bill. And I expect that in the next annual cycle, when a report is submitted, that goals for hydrogen will be included, as would be goals for all of the other technologies.

In addition, part of the hydrogen goal formulation process has been evolving as we have been developing the required multi-year program plan for several pieces of existing legislation.

Senator FORD. Doctor, it is awful easy to confuse a person like me, who is not educated in the scientific field. Are we nickel and diming a lot of projects just to kind of satisfy some people, or are we really selecting those that have a near-term effect, and are beginning to move with those much faster than we would those that would be way out in the future, the middle of the next century or something?

Dr. SAN MARTIN. Mr. Chairman, we are also very, very concerned about nickel and diming too many areas in energy. Energy is too important a topic to dabble in many areas. There should be significant enough efforts in the areas that we collectively feel are most important in this country, and then proceed with them at all due pace.

In the hydrogen arena specifically, I think that there are many ways in which the work that is currently ongoing supports the promise of hydrogen. There is direct work that is going on that has proceeded at a nominal $4 million a year that is very directly related to the production of hydrogen. But, as I have argued before in prior testimony on this topic, the future of hydrogen in many ways is tied to there being economically available renewable energy resources that can produce energy at competitive costs.

And, in that regard, there is a rather substantial program that is developing the renewable resources. In addition to that, a most promising way for the utilization of hydrogen is in fuel cell technology, and there is a substantial fuel cell program under way. So, if I look at the commitment and the programs that go on in the Department of Energy dealing with the development of renewable energy resources, fuel cell technology and hydrogen all summed up, you have an activity of over $150 million a year that is taking place.

Senator FORD. You said in your statement that a demonstration program is premature at this time. I believe you said that, and that this bill would limit the Department's flexibility in the ongoing research and development efforts. The Matsunaga bill passed in the previous Congress mandated certain actions, I believe, to be taken in the area of hydrogen research and development. Some of these actions have been taken and some have not. Help me out in finding the middle ground. What is the next step and what do you do then to take it, or what do we do to make you take it or encourage you to take it, or something in that area?

Dr. SAN MARTIN. Mr. Chairman, as far as the Department is concerned, I think some of the next steps are under way. They have

not evolved as fast as would satisfy us both, but I believe they are in progress. Step No. 1, which was required by the Matsunaga bill, was the establishment of an advisory committee on this particular topic. We are in the final phases of in fact creating that advisory committee, which is a key component of a group to work with the Department to actually review and comment for us on items such as the multi-year plan that is required by the act itself, which will be a key document in guiding the future of the hydrogen program.

So I believe the fact that this is not only under way, but we are at the 11th hour of making the appointments and starting meetings of this committee, and being able to present a multi-year plan, and then also present it to the Congress, are the key steps to then unfold the remainder of the hydrogen program.

Senator FORD. The Matsunaga Hydrogen Act required the Department to develop a management plan for hydrogen research and development. And that committee is needed to be formed so that they can develop a plan. I believe the bill stated that you would have that in place by May 15, of this year. It is obvious that you are not going to meet that deadline. When will the management plan be finished?

Dr. SAN MARTIN. We expect that the management plan will be finished and be able to be submitted to the Congress by the end of August. And we anticipate that the advisory committee can be appointed within the next 30 days, Mr. Chairman.

Senator FORD. I have several other questions, Doctor, that I will submit to you in writing.

A couple of final questions, though. Do you know how much other countries are spending on hydrogen, and what does the DOE think of those efforts?

Dr. SAN MARTIN. Mr. Chairman, I think we have a good sense of what is going on in expenditures in other countries. We also are involved in an international collaborative effort with all of the major countries that are involved in the development of hydrogen technology. We do this through a multilateral agreement we have with the International Energy Agency that involves a couple of handfuls of countries, but the lead countries being Germany, Canada, Japan, and the United States as the ones that have the largest programs. And we confer with our colleagues that lead their respective national programs a couple of times a year.

I might caution, though, based on lots of data that I have seen quoted, many times some parties in one country will announce a program that they intend to undertake in the future, and it is not a commitment where their parliament or their governing body has yet appropriated funds. Also, there are other countries that announce some rather large programs that are programs that are intended over 5 or 10 years, so on an annual basis you have a different expenditure rate.

So, as you review this type of data, I would just share a little bit of caution in looking at it so that we are comparing oranges with oranges in that process. Because there is interest and there are major investments taking place in other countries in renewable resources, in fuel cell development, and there are investments taking place in hydrogen also.

Senator FORD. Doctor, would you be willing to work with the committee to develop amendments to this bill that would make it a vehicle for taking the appropriate next step in hydrogen research and development?

Dr. SAN MARTIN. Mr. Chairman, in the spirit of cooperation, we would be most happy to work with the committee to see if something can be structured to our mutual satisfaction.

Senator FORD. Well, let us see if we cannot begin to use a little old Henry Clay on it and not kill Zachary Taylor, but work out something that will put us a little further along the way. Doctor, you are mighty nice to have come today and I appreciate your cooperation, and we look forward to working with you.

Dr. SAN MARTIN. Thank you very much, Mr. Chairman.

Senator FORD. Next will be a panel that will be made up of Dr. James Birk, director, Storage and Renewables Department, Electric Power Research Institute; Dr. Jeffrey A. Serfass, president, National Hydrogen Association; Dr. Keith Prater, vice president of technology, Ballard Power Systems; and Dr. Joan Ogden, Center for Energy and Environmental Studies from Princeton University.

Good morning, lady and gentlemen. We are delighted to have you with us this morning, and I believe I will take Dr. Ogden first and let you make your statement. And, if you recall earlier, this panel will have to be over in about an hour, so let us see if we cannot move right along and get some questions answered for the record. Then, as I said earlier, there will be questions in writing that will be submitted to you, and I hope that you will respond to us in a timely manner. Then we can start working with the Department to see if we can work out a piece of legislation that would be acceptable.

So, Dr. Ogden, please proceed.

STATEMENT OF DR. JOAN M. OGDEN, CENTER FOR ENERGY AND ENVIRONMENTAL STUDIES, PRINCETON UNIVERSITY, PRINCETON, NJ

Dr. OGDEN. Thank you, Mr. Chairman.

I am pleased to have the opportunity to testify at this hearing on the proposed Renewable Hydrogen Energy Research and Development Act. I am a research physicist at Princeton University's Center for Energy and Environmental Studies, and since 1985 I have been studying the prospects for producing hydrogen from solar sources and using it for various purposes, including transportation, power generation, and home heating. I am coauthor of a report entitled Solar Hydrogen: Moving Beyond Fossil Fuels. Researchers at our center are currently studying hydrogen production from coal and biomass and hydrogen fuel cell cars.

First, I would like to briefly summarize our views on the prospects for renewable hydrogen production and use. Concerns about urban air quality, acid deposition and global warming, as well as energy supply security, are motivating renewed interest in low polluting, domestically available alternatives to fossil fuels. And hydrogen is attractive as a possible alternative for several reasons.

First, it is a high quality, exceptionally clean burning fuel. The technical feasibility of using hydrogen has already been demon-

strated in prototype cars, buses, airplanes, home heating systems, and power generation systems. When hydrogen is burned in air, the primary emission is water vapor, and the only pollutants would be low levels of nitrogen oxides. With hydrogen fuel cell technology which is being developed, even NO_x emissions would be eliminated.

Hydrogen could be produced domestically from a variety of renewable sources, including biomass gasification or water electrolysis using hydroelectric, wind or solar power. The United States has abundant resources for renewable hydrogen production and it would be possible to supply hydrogen energy on a national scale with negligible greenhouse gas emissions, very low pollution, and no dependence on foreign energy supplies.

Most of the technologies needed to build renewable hydrogen production systems have already been demonstrated and are commercially available. At present, the main barrier to producing renewable hydrogen is the cost. However, costs are projected to drop considerably over the next 10 to 20 years.

In the 1990's, biomass gasification and electrolysis using off-peak hydropower would probably be the least expensive methods of producing renewable hydrogen. We estimate that biomass hydrogen could be delivered to the consumer for transportation use at a filling station at a cost of about $12 per million Btu, or equivalent to about $1.60 per gallon of gasoline. Hydrogen from hydropower might cost $2 to $3 a gallon of gasoline equivalent. And by the late 1990's or the early part of the next century, electrolytic hydrogen from wind and solar photovoltaic sources should reach similar costs.

Opportunities could open to introduce hydrogen as a clean transportation fuel in the United States over the next 10 years. The California Air Resources Board has mandated that zero emissions vehicles must be phased in starting 1998. The only zero emissions vehicles which could be developed in this time frame would be electric battery cars and hydrogen fuel cell cars. Hydrogen fuel cell cars would be particularly attractive because they could be general purpose vehicles, having a longer range, say, 200 to 250 miles, as compared to maybe 100 to 200 for battery electric cars, and a much shorter refueling time, 5 to 7 minutes, compared to several hours recharging time for batteries.

For cars with a 250-mile range, we estimate the life cycle cost of owning and operating a hydrogen fuel cell vehicle will be substantially less than that for an electric battery vehicle. And even though fuel cell cars would be more expensive than gasoline cars and renewable hydrogen would cost more than gasoline, the life cycle cost of a hydrogen fuel cell vehicle would be only slightly more than or maybe even comparable to a gasoline vehicle. This would be true because hydrogen fuel cell cars would be about twice as efficient as gasoline cars, so that the fuel cost per mile would be the same if hydrogen cost twice as much as gasoline.

Fuel costs also are only a small fraction, maybe 10 to 20 percent of the total cost of transportation. So higher fuel costs would have only a modest impact on total cost. And finally, fuel cell vehicles would be more expensive, but they would last longer and require less maintenance.

Now I would like to make some comments on the proposed bill. The bill proposes several points. First, they propose renewable hydrogen R&D programs; second, formulation of a multi-year plan for development of renewable hydrogen; and third, joint venture demonstration projects in renewable hydrogen energy systems. The bill goes beyond the Matsunaga Act in that specific promising renewable hydrogen technologies are targeted for evaluation, research and development.

I support this bill for several reasons. First, the proposed R&D programs would include important topics which are not being adequately funded or addressed within existing DOE hydrogen programs. The bill would provide a much needed program to build and test systems for generating hydrogen from renewable resources. DOE does basic science experiments on long-term renewal hydrogen concepts, such as photoelectric chemical and photobiological hydrogen production, but there is very little support for renewable hydrogen production from systems that have a good chance of becoming economically interesting in the next 20 years. And I would include biomass gasification, electrolysis power by hydro, wind, and solar in that category.

Also, the bill provides for a program to build and test key hydrogen end-use technologies, including on-board storage systems and fuel cells for hydrogen vehicles, both essential topics which deserve more support. It would be important here to coordinate with ongoing activities within other parts of DOE, as Dr. San Martin testified is happening on fuel cell research.

Second, DOE's renewable hydrogen program needs to be focused through development of a multi-year comprehensive plan for R&D, and the bill would accomplish this goal.

And, third, renewable hydrogen energy systems joint venture demonstration projects are timely and appropriate in my opinion. The technologies are ready to be demonstrated, and our estimates indicate that renewable hydrogen could become economically interesting as a clean transport fuel in the next 10 to 20 years. In fact, several such demonstration projects are already under way or proposed in Germany, Canada, and the United States. One of the biggest ones is a $50 million total program in Germany, where a solar photovoltaic electrolyzer is being built by a consortium of industry, utility, and government partners. In addition, there are a number of transportation projects under way.

Finally, just to sum up. I think renewable hydrogen is potentially important energy supply option, and DOE's present program of renewable hydrogen energy could be greatly improved if the proposed bill were implemented.

Thank you.

[The prepared statement of Dr. Ogden follows:]

PREPARED STATEMENT OF DR. JOAN M. OGDEN, CENTER FOR ENERGY AND ENVIRONMENTAL STUDIES, PRINCETON UNIVERSITY, PRINCETON, NJ

INTRODUCTION

Mr. Chairman, I am pleased to have the opportunity to comment on the prospects for production and use of hydrogen from renewable energy sources, at this hearing on the proposed Renewable Hydrogen Energy Research and Development Act of 1991.

I am a research physicist at Princeton University's Center for Energy and Environmental Studies. Since 1985, I have been studying the technical and economic outlook for producing hydrogen from renewable sources and using it for various purposes including transportation, power generation, home heating, and industrial uses. I am coauthor (with Princeton colleague Robert Williams) of a book entitled "Solar Hydrogen: Moving Beyond Fossil Fuels," which was published by the World Resources Institute in 1989. Other ongoing hydrogen research at our Center includes assessments of hydrogen production from coal and biomass, and assessments of hydrogen fuel cell cars.

Before giving specific comments on the proposed bill, I would like to present some background material, based on our work at Princeton, which summarizes our views on the prospects for production of hydrogen from renewable resources and its use in various applications. This discussion provides the basis for my comments on the bill.

PROSPECTS FOR RENEWABLE HYDROGEN ENERGY SYSTEMS

Motivations for the development of renewable hydrogen energy systems

Concerns about urban air quality, acid deposition and global warming, as well as security of energy supply are leading to renewed interest in low polluting, domestically available alternatives to fossil fuels. Hydrogen is attractive as a possible alternative because:

- Hydrogen is a high quality, exceptionally clean burning fuel, which could replace fossil fuels for transportation, heating and power generation. The technical feasibility of using hydrogen has already been proven in prototype cars, buses, airplanes, home heating systems and power generation systems.
- With hydrogen fuel, the primary exhaust product is water vapor. Most of the harmful emissions associated with fossil fuel use would be eliminated: no carbon monoxide, unburned hydrocarbons, particulates, sulfur oxides, carbon dioxide or other greenhouse gases would be emitted. When hydrogen is burned in air (as in internal combustion engines or hydrogen flame burners), the only pollutants produced would be oxides of nitrogen (NO_x), which could be controlled to low levels. With hydrogen fuel cells or catalytic heating systems, even NO_x emissions would be eliminated.
- Hydrogen could be produced domestically from a variety of renewable sources, including gasification of renewably grown biomass or water electrolysis using solar, wind or hydroelectric power. The United States has abundant resources for renewable hydrogen production. It would be possible in principle to supply hydrogen energy on a national scale, without serious land or water constraints.
- If hydrogen is produced from renewable sources, it would be possible to have a large scale energy system with negligible greenhouse gas emissions, very low local pollution, and no dependence on foreign energy supplies.

Technologies for renewable hydrogen production

In renewable electrolytic hydrogen systems, a source of renewable electricity (solar photovoltaics, solar thermal, wind or hydroelectric) is connected to an electrolyzer, which splits water into its constituent elements hydrogen and oxygen. Hydrogen can be used onsite, compressed for storage or transmitted via pipelines to distant users (as an example, Figure 1 shows a solar photovoltaic hydrogen system).

Hydrogen can also be produced by gasifying at high temperatures, biomass feedstocks such as forest and agricultural residues or wood chips. The gasifier output, consisting mainly of hydrogen, carbon monoxide and methane can then be reformed and shifted to produce a mixture of hydrogen plus carbon dioxide. The carbon dioxide is then removed, leaving hydrogen.

Most of the components needed to build renewable hydrogen production systems have already been demonstrated and are commercially available. At present, the main barrier to producing renewable hydrogen is cost rather than technical feasibility. However, costs are expected to drop considerably over the next ten to twenty years.

- Intermittent solar electric technologies, including solar photovoltaics, solar thermal electric systems and wind power are undergoing rapid technical progress and commercialization and are moving into increasingly large electricity markets. As technology improves and the scale of production increases, the costs of solar electricity are projected to drop significantly over the next ten to twenty years. Current electricity production costs for these technologies and projections for the near term (1990s) and early 2000s are given in Table 1. Post 2000 projections for these technologies suggest that intermittent electricity at the power plant site without storage could cost as little as 2-5 cents/kWh.

- Hydroelectricity is a mature, commercial electric generation technology. At sites where there is excess off-peak power available, hydro power can be very inexpensive, making it attractive for electrolytic hydrogen production.
- Water electrolysis is a mature, commercial technology. While most electrolyzers today are small, a few installations of 10 MW or more have been built, mostly near hydroelectric plants, where inexpensive electricity is available.
- Biomass gasifiers have been demonstrated at the laboratory and pilot plant scale. Several biomass gasifiers under development in the U.S., mainly for methanol production, are probably suitable for hydrogen production as well. All the equipment needed for converting the gasifier output to hydrogen (methane reformers, shift reactors, CO removal technology, pressure swing adsorption technology for hydrogen purification) is well-established commercial technology in the chemical process industries.

Economics of renewable hydrogen production

The production cost of renewable hydrogen from various sources is estimated in Table 2 for present, near term and post 2000 technologies.

Hydrogen production costs are given in units of 1989 US$ per Gigajoule of energy, based on the higher heating value of the fuel. One Gigajoule of hydrogen is equivalent in energy to about 7.7 gallons of gasoline. The present wholesale gasoline price of 70 cents/gallon is equivalent to $5.4/GJ. At the projected year 2000 world oil price of $27.8/barrel, the wholesale gasoline price would be about 84 cents/gallon or $6.5/GJ.)

As Table 2 shows, the cost of renewable hydrogen is projected to decrease markedly over the next ten to twenty years.

- In the 1990s, biomass gasification might be the least expensive source of renewable hydrogen, costing about $7/GJ to produce, according to recent estimates by the Hawaii Natural Energy Institute. (This is only slightly higher than the wholesale gasoline price projected for the year 2000.) While land and water requirements for biomass hydrogen production would be considerably larger than for wind or solar electrolysis (Table 3), biomass could be produced on a large enough scale to displace a major fraction of future U.S. oil use. (Assuming that efficient hydrogen fuel cell cars are developed, only about 3.5 Quads of biomass feedstock would be needed to produce enough hydrogen to fuel U.S. cars and light trucks at the 1987 level of driving. The 1990 DOE Interlaboratory White Paper on the Potential of Renewable Energy estimates that recoverable energy from biomass in the U.S. could be 14.6 Quads/yr by the year 2000.) Biomass gasification also has the advantage of a lower capital cost than more capital intensive technologies such as PV and wind electrolysis.
- Hydro electricity is currently used for electrolytic hydrogen production at a few sites around the world, where cheap excess power is available. Many of the best hydro sites in the U.S. have already been exploited and further development might be difficult because of environmental and land constraints. In the long term the contribution of hydro would be relatively small and renewable hydrogen in the U.S. would have to come mainly from other sources. Still, off-peak hydropower at existing sites might offer an opportunity to help launch electrolytic hydrogen as an energy carrier. If electricity were available for 2-4 cents/kwh during nighttime hours, the cost of hydrogen would be about $12-20/GJ.
- Wind power will probably be the least costly intermittent solar electricity by the mid to late 1990s. Rapid progress is being made in a variety of wind technologies. The next generation (1995) of wind turbines are expected to produce electricity at a cost of 5 cents/kWh at a good site in the Great Plains. In the longer term (c. 2000) costs of 3 cents/kWhAC might be achieved. From preliminary calculations, we estimate that electrolytic hydrogen would then cost $12-15/GJ to produce. Land requirements for wind power would be about 3-4 times greater than those for solar PV, but it might be possible to use the land for other purposes such as grazing cattle or agriculture. Moreover, good wind resources exist in many regions of the U.S. with low insolation.
- While solar PV hydrogen is likely to be more expensive than other sources of renewable hydrogen for the next ten to twenty years, it is important as a potential long term supply option, because production would be the least constrained by resource availability, land or water requirements. (Land requirements would be 20-30 less than those for biomass, and water requirements would be several hundred times smaller. It would be possible to produce PV hydrogen even in a desert.) By the early part of the next century, solar photovoltaic hydrogen produced in the Southwestern U.S. could cost as little as $10-16/GJ. This would be

comparable in cost to liquid synthetic fuels from coal or biomass, which are projected to cost $9-17/GJ.

- In comparing fuel costs, it is important to note that for some applications, it would be possible to use hydrogen more efficiently than other fuels. For example, a hydrogen fuel cell car would be about twice as efficient as a gasoline powered internal combustion engine car. Hydrogen at $14/GJ would give the same fuel cost per mile as gasoline at $7/GJ. Moreover, even though fuel cells would be more capital intensive than gasoline cars, they would last longer and require less maintenance. On a lifecycle cost basis, even higher cost wind or electrolytic hydrogen could compete with gasoline, if used in fuel cell cars.

Hydrogen as a transportation fuel

The first major energy market for hydrogen is likely to be as a clean transportation fuel. In my discussion, I will concentrate on this application, though hydrogen could also be used for power generation, cogeneration and heating.

The technical feasibility of using hydrogen in transportation has been demonstrated in automobiles, buses, trucks and airplanes. In Germany, Daimler-Benz and BMW have ongoing programs in hydrogen vehicle research. Daimler-Benz operated a fleet of five hydrogen vans and five dual fuel hydrogen/gasoline cars in Berlin, accumulating over 250,000 km of experience in a five year period. Experimental hydrogen vehicles have also been built in the U.S., Japan, the Soviet Union, Romania, Canada, New Zealand and Australia.

Opportunities could open to introduce hydrogen as a clean transport fuel over the next ten years. It is significant for hydrogen that the California Air Resources Board has mandated that starting in 1998, 2% of passenger cars and light trucks sold must be "zero emissions vehicles" (ZEVs). By 2001 5% of cars sold must be ZEVs and by 2003 10%. The only vehicles which could be developed in this time frame to meet the potentially huge market for ZEVs would be electric battery cars and hydrogen fuel cell cars.

Research and vehicle tests to date have shown that fuel storage is the major technical challenge facing hydrogen as a transport fuel. Unlike liquid fuels such as gasoline, Diesel or methanol, hydrogen is not easily stored at ambient pressure and temperature. Hydrogen can be stored onboard the vehicle in compressed gas cylinders, as a cryogenic liquid (at -253°C) in dewars, or as a metal hydride (a compound which absorbs hydrogen under pressure and releases it when heat is applied). All these storage systems are heavier and bulkier than those for gasoline or methanol, (although they are lighter and more compact than even advanced electric batteries), so that storing enough energy onboard for a reasonable travelling range is a major challenge. Although liquid hydrogen has a relatively high energy density, liquefication is expensive and fuel distribution and dispensing are problematic because of the very low temperatures required. The amount of fuel and hence the size of the fuel storage system required for a given range depends on the vehicle efficiency. It is important to make hydrogen vehicles as efficient as possible to maximize the vehicle travelling range.

Storage constraints could be eased if the hydrogen were used in a fuel cell that converts hydrogen fuel energy directly into electricity, rather than in an internal combustion engine (most experimental hydrogen cars to date have used ICEs). The output of the fuel cell would power an electric drive train, the same as that of an electric car. Like electric battery cars, hydrogen fuel cell cars would be "zero emissions vehicles". Moreover, it is estimated that a hydrogen fuel cell vehicle could achieve 2 to 2.5 times the efficiency of comparable gasoline internal combustion vehicles. Because fuel cell cars would be highly efficient, a travelling range of 200-250 miles should be possible. In a hydrogen fuel cell car, it would be possible to use onboard compressed gas storage, which offers the advantages of simplicity and speed in refueling (hydrogen cars could be refueled in 5-7 minutes at a compressed gas filling station). This contrasts with the battery powered electric car, where storage constraints would limit the range to 100-150 miles, even with advanced batteries, and recharging would take several hours. The hydrogen fuel cell vehicle can be viewed as a more flexible ZEV.

Hydrogen fuel cell vehicles would benefit from ongoing research on electric battery cars, as many of the electric drive train components would be the same. Gaseous storage and refueling technologies similar to those developed for compressed natural gas cars could be used for hydrogen.

Several types of fuel cells are now under development for automotive applications. One of the most promising technologies appears to be proton exchange membrane (PEM) fuel cells. PEM fuel cells could offer the high power density and low cost required for automotive power systems. At present, fuel cell vehicles are being devel-

oped by DOE and various industry partners for use with methanol fuel. The fuel cells would also be suitable for use with hydrogen, but there is currently no focussed hydrogen fuel cell vehicle program within DOE. However, several groups have proposed to build prototype hydrogen fuel cell vehicles. These include Ballard Technologies (Canada), Energy Partners (Florida), Elenco (Belgium) and the Pennsylvania Energy Office with Roger Billings. The South Coast Air Quality Management District has recently begun a project to produce hydrogen via PV powered electrolysis for use first in IC engine hydrogen vehicles and later in fuel cell vehicles.

All fuel cells utilize the hydrogen in fuel and the oxygen in air to generate electricity. When a fuel other than pure hydrogen is used, it must be converted to hydrogen by passing through a "reformer," on its way to the fuel cell. In a methanol car, the onboard reformer is a bulky piece of equipment, which adds extra complexity and cost, and decreases efficiency and performance. In methanol fuel cell cars it is difficult to achieve good acceleration, because the reformer does not respond quickly enough to an increased load. Hydrogen fuel cell vehicles would avoid some of the complexities inherent in methanol fuel cell vehicles (the need for an onboard reformer), and would be more efficient, but onboard storage would be more difficult than with methanol.

Preliminary analysis shows that the lifecycle cost of owning and operating a hydrogen fuel cell vehicle with a 250 mile range would be only slightly more than that of a gasoline vehicle, and much less than that of a battery electric vehicle with a 250 miles range (Figure 2).

Summary: The Outlook for Renewable Hydrogen

- It is technically feasible to produce large quantities of hydrogen from a variety of domestically available renewable resources, including water electrolysis powered by solar, wind or hydroelectricity and biomass gasification. Large biomass sources could be developed, and both wind and especially solar resources are potentially vast, and could in the long term supply all the hydrogen required.
- Renewable hydrogen energy systems could be environmentally attractive, with essentially no emissions of greenhouse gases or other harmful pollutants.
- At present the main barriers to producing renewable hydrogen are economic rather than technical. However, the cost of renewable hydrogen is projected to drop significantly during the next ten to twenty years. In the 1990s, hydrogen from biomass gasification would probably be the least expensive supply of renewable hydrogen. Electrolytic hydrogen from off-peak hydropower might also be relatively inexpensive. Wind electrolytic hydrogen would probably become relatively low cost in the mid to late 1990s. In the early part of the next century, electrolytic hydrogen from solar PV would probably become cost competitive with wind hydrogen.
- For renewable hydrogen production costs of $7-16/GJ, costs projected for several technologies over the next ten to twenty years, the lifecycle cost of using hydrogen for applications such as transportation and heating would be comparable to the cost of using other fuels, if energy efficiency is stressed.
- Opportunities to introduce hydrogen as a clean transport fuel could begin in the next ten years. Low polluting hydrogen internal combustion experimental vehicles have already been built. Hydrogen fuel cell vehicles, which could be developed in the next few years, would combine the best features of battery electric vehicles (zero emissions, quiet, low maintenance) with the flexibility of gasoline vehicles (long range, fast refueling time). Preliminary studies suggest that renewable hydrogen would be economically competitive as a clean automotive fuel, if used in fuel cell vehicles. The lifecycle cost (cents/mile) for hydrogen fuel cell vehicles with a 250 mile range would be significantly less than that of an electric battery vehicle and comparable to that of a gasoline vehicle.

COMMENTS ON THE PROPOSED BILL

Support for the findings of the bill, Section 2

Our research results strongly support the findings in Section 2 of the bill. In particular, that it is technically feasible to manufacture hydrogen domestically from a variety of renewable sources and use it in efficient, low polluting vehicles, heating systems and power systems. Renewable hydrogen energy systems could offer important environmental and energy supply benefits. Further, based on projections for technologies for producing hydrogen from biomass gasification, or electrolysis powered by off-peak hydroelectricity wind or solar PV, our studies show that renewable hydrogen could become approximately cost competitive with other fuels or electricity for applications such as transportation over the next ten to twenty years, if efficient end-use technologies such as fuel cell vehicles were used.

Comments on the proposed R&D program, Section 5(a)

The proposed R&D programs in Section 5(a) would address a number of important issues for development of renewable hydrogen energy systems, which are not being adequately funded or addressed within existing DOE hydrogen programs. These are listed in subsections (1)-(5) of bill. Comments on each of these five subsections are given below.

(1) The bill would provide a much needed program to build and test systems for generating hydrogen from renewable resources. Within existing DOE programs, laboratory scale, basic science experiments on long term, highly uncertain renewable hydrogen concepts such as photoelectrochemical and photobiological hydrogen production are supported, but there is very little DOE supported work involving renewable hydrogen production from systems that have a good chance of becoming economically interesting in the next ten to twenty years (biomass gasification, electrolysis powered by hydro, wind and solar). This contrasts with R&D programs in Germany where a $50 million PV hydrogen project is underway, or Canada, where a $100 million hydro/hydrogen project is proposed. As far as I know, there is one small operating PV hydrogen system in the U.S., located at Humboldt State College, (which receives some funds from SERI through the PV program, but is mostly privately funded), another small PV hydrogen system being designed by a Canadian company, Electrolyzer, Inc. in a joint venture with SCAQMD, and some laboratory work on novel schemes for producing hydrogen from biomass gasification at Hawaii Natural Energy Institute (funded by the DOE Hydrogen Program). There is currently no work on hydrogen from wind power. There is also no DOE program on electrolysis technology. Even though the separate components of wind and PV electrolysis systems have been tested, it is important to understand how they function as a system. There is ongoing DOE research on biomass gasification for methanol production, which would probably apply to biomass hydrogen production as well. This might give the hydrogen program a chance to "piggyback" on ongoing biomass gasification work. It would be interesting to compare methanol and hydrogen as alternative routes for production and utilization of biofuels in fuel cell cars.

(2) The bill provides for a program to build and test hydrogen catalytic burners. Hydrogen fueled catalytic combustion appliances are being developed in Germany, and have been researched in the U.S., Japan and Europe. This is an interesting area for research as catalytic systems would produce no pollutants.

(3) The bill provides for evaluating the ability of existing natural gas lines to carry hydrogen, either in mixtures or as pure hydrogen. Experiments to study hydrogen gas distribution systems are important. Natural gas is often suggested as a "transition" fuel toward development of hydrogen. Understanding how much of the existing infrastructure could be used for hydrogen would be interesting. Safety issues might also be addressed here.

(4) The bill provides for at least one program to build and test storage systems suitable for use with fuel cell vehicles. Onboard hydrogen storage for vehicles is perhaps the most important major challenge facing hydrogen as a transport fuel. It is crucially important to continue and expand R&D on this topic, and to explore new concepts for hydrogen storage. The focus on storage systems specifically for fuel cell vehicles is well placed, given the potential of this technology.

(5) The bill provides for development of a hydrogen fuel cell for vehicle applications. Hydrogen fuel cell vehicles are a key technology which should receive the highest priority. It would be important here to coordinate with ongoing activities within other parts of DOE, which currently support fuel cell research and development, including fuel cells for methanol, which could also be used with hydrogen.

Comments on the proposed multi-year plan for development of renewable hydrogen, Section 5(b)

This section specifies the issues which should be addressed in the proposed plan for development of renewable hydrogen. The list of proposed topics is comprehensive and mentions what I see as the most crucial issues which should be evaluated in the process of writing the plan. My only suggestion to improve this plan would be to mention biomass gasification as a renewable hydrogen production system to be evaluated (Section (A-i)

Comments on joint venture demonstration projects

Joint ventures are proposed in renewable hydrogen production and in two applications: utility load leveling and transportation. In my view various technologies for hydrogen production and use are technically ready to be demonstrated. In fact several demonstration projects on renewable hydrogen production and hydrogen use are already underway or proposed. Renewable hydrogen production projects include:

- The $50 million Solar Wasserstoff Solar Hydrogen Project in Germany, a 500 kW solar PV powered electrolyzer being built by a consortium of industry, utility and government partners.
- The 350 kW "Hysolar" PV electrolysis system, which has been built in a joint venture between Germany and Saudi Arabia.
- A 10 kW experiment at DLR, the German aerospace laboratory.
- In the U.S., a 10 kW experimental PV hydrogen system is operating at Humboldt State College,
- SCAQMD and Electrolyzer, Inc. of Canada have a joint venture to build a small PV hydrogen system and use the hydrogen in vehicles.
- A group of Canadian and German interests are proposing a $100 million "Euro/Quebec Project" to produce hydrogen from off-peak Canadian hydropower, and ship the hydrogen to Germany for use as a transport fuel.

In addition hydrogen transportation projects are underway or planned:

- Mercedes Benz and BMW both have hydrogen vehicle research and testing programs.
- Several groups are proposing to develop hydrogen fuel cell vehicles over the next few years. These include Ballard Technologies (Canada), Energy Partners (Florida), Elenco (Belgium) and the Pennsylvania Energy Office with Roger Billings, and the South Coast Air Quality Management District (California).

Although the various components which make up a renewable hydrogen energy system are well understood, it is important to understand how various technologies would function together. Much could be learned about renewable hydrogen systems from several well designed demonstration projects, aimed at addressing critical systems issues.

In the area of renewable hydrogen production, issues of coupling a PV array or wind power system to an electrolyzer should be investigated. When electrolyzers operate under intermittent sources such as solar or wind, issues of electrode lifetime under cycling might become important. At present, there is little data on this topic.

Biomass gasification technology is currently being studied for methanol production. Some of this work would be applicable to hydrogen production, as well. A hydrogen biomass gasification project could build on current methanol projects.

For fuel cell vehicles, a number of questions regarding vehicle design remain, as well as refueling systems and storage. The two or three demonstration projects already being planned could be the first step in a well-coordinated, long-range research, development, and demonstration plan for hydrogen fuel cell vehicles. This program will help investigators maximize the performance of fuel cell vehicles, minimize their cost, and make them suitable for mass production and mass marketing. Specifically, a comprehensive, long-range R&D&D program will provide the opportunity to:

- Build a fuel cell vehicle from the ground up, and test different chassis and body designs, to optimize performance and efficiency.
- Experiment with different arrangements of the battery, the fuel cell, the hydrogen fuel-storage equipment, the electric motor, and the controller, to maximize the space available for passengers and luggage.
- Test different ways of electronically integrating the various components to maximize power output, energy efficiency, system reliability, and response to power demand.
- Design a system that efficiently manages air, water, heat, and fuel flows in the fuel cell.
- Determine the best way to store hydrogen onboard fuel cell vehicles.
- Design and test refueling technology for fuel cell vehicles.
- Learn how consumers would react to the new technology.

SUMMARY

I support passage of the Renewable Hydrogen Research and Development Act for several reasons.

(1) Renewable hydrogen systems offer many potential environmental and energy supply advantages. The U.S. is rich in renewable resources and could produce as much renewable hydrogen as it needed for transportation, heating or power. At present, DOE's Hydrogen program is not adequately funding research on renewable hydrogen production methods (such as biomass gasification and electrolysis powered by hydro, wind or solar electricity), which could become economically attractive over the next ten to twenty years. Nor is it funding research on key end-use technologies such as hydrogen fuel cell vehicles. DOE's renewable hydrogen program needs to be focussed through development of a comprehensive plan for R&D. The proposed bill would accomplish this goal. The bill would go further than the Matsunaga Act, in

that specific promising renewable technologies, are targeted for evaluation, research and development and demonstration. I would suggest that the prospects for biomass gasification should be evaluated, given its apparent potential to reach low costs in the next ten years.

(2) Our analyses suggest that hydrogen fuel could become economically competitive as a clean transport fuel in the next ten to twenty years. At present electrolytic hydrogen from solar or wind resources would be much more expensive than other fuels. However, hydrogen could be produced from other renewable resources (biomass, off-peak hydro) at a cost comparable to that of other fuels starting in the mid to late 1990s. By the late 1990s or early 2000s, wind and PV should reach relatively low costs as well. For hydrogen production costs projected for the next ten to twenty years, the lifecycle cost of using hydrogen as a automotive transport fuel in fuel cell vehicles would be competitive with the costs of electric battery vehicles and gasoline powered vehicles.

(3) Technologies for producing and using renewable hydrogen are ready for demonstration. They are already being demonstrated in Germany and the U.S. Demonstration projects should be aimed at addressing particular systems issues (for example, for PV electrolysis, lifetime and behavior of electrolyzer with an intermittent (solar) power source; for fuel cell vehicles, vehicle design, refueling technology and storage; for biomass gasifiers understanding how hydrogen and methanol would compare as energy carriers.)

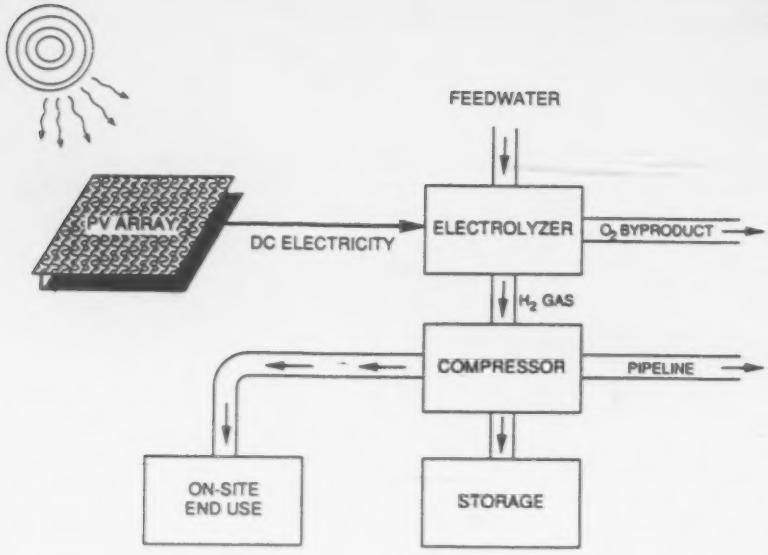


Figure 1. A solar photovoltaic electrolytic hydrogen system

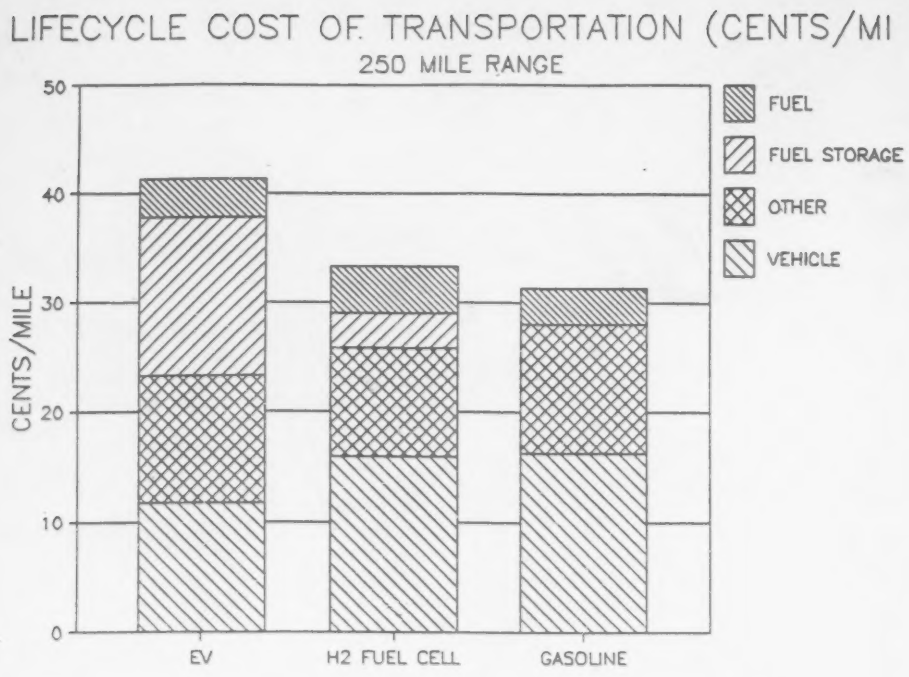


Figure 2. Lifecycle cost of transportation for electric battery vehicles, hydrogen fuel cell vehicles and gasoline powered vehicles, assuming a 250 mile range. The delivered cost of electricity is assumed to be 8.8 cents/kWh, the cost of hydrogen (assumed to be from c. 2000 wind or solar electrolysis) is taken to be $22.7/GJ (equivalent to $3.1/gallon gasoline), and the cost of gasoline is $1/gallon. Taxes are excluded from fuel costs. Hydrogen fuel cell vehicles have a lifecycle cost considerably less than that of electric battery cars and only slightly higher than that of gasoline powered cars.

With biomass gasifier systems, the delivered cost of hydrogen would be about $11.5/GJ ($1.6/gallon gasoline). In that case, the lifecycle cost transportation for the hydrogen fuel cell vehicle would be about the same as that for the gasoline vehicle.

TABLE 1. PROJECTED SOLAR ELECTRICITY COSTS (CENTS/KWH)

TECHNOLOGY	1990	1990'S	POST 2000
WIND (GREAT PLAINS)	6	4-5	2.5-3.2
SOLAR THERMAL ELECTRIC (SW)	13-14	6-8	5
SOLAR PV (SW)	12-30	6-12	2-4

ASSUMING REAL 6% DISCOUNT RATE, NO TAXES INCLUDED.

Table 2. Current and Projected Production Costs of Renewable Hydrogen ($/GJ)

	1991	Near Term	Post 2000
Electrolytic Hydrogen from:			
PV (SW)	40-55	23-44	10-16
Wind (Great Plains)	26	17	12-15
Solar Thermal (SW)	45-55	24-30	21
Hydroelectricity off-peak at existing site (@ 2 - 4 cents/kwh)	12-20	12-20	12-20
Hydrogen from Biomass Gasification: (assuming feedstock cost of $2/GJ)		7	7

TABLE 3. LAND AND WATER REQUIREMENTS FOR RENEWABLE HYDROGEN PRODUCTION

	LAND REQUIREMENTS		WATER REQUIREMENTS
Electrolytic hydrogen from:	$MJ/yr/m^2$	To produce H2 for fuel cell cars [e] (km^2)	liters/GJ (HHV)
Solar photovoltaics [a]	530	5700	63
Wind [b]	200	15,000	63
Hydroelectric [c]	2-90	-	63
Biomass Hydrogen [d]	13	230,000	23,000-54,000

[a] It is assumed that a fixed, flat plate solar photovoltaic system is used, with array spacing so that 1/2 the land area is covered by arrays. The efficiency of the PV array is assumed to be 15%, the DC electrolyzer efficiency is taken to be 80%, based on the higher heating value of hydrogen, and the coupling efficiency between the PV array and the electrolyzer is taken to be 96%. Annual energy production is given for a Southwestern US location with average annual insolation of 271 $Watts/m^2$. Water requirements are for electrolyzer feedwater.

[b] It is assumed that an array of 25 meter diameter 200 kW wind turbines is used. The wind turbine spacing is assumed to be 1.5 diameters in the direction perpendicular to the prevailing wind and 10 diametrs in the direction parallel to the prevailing wind. An electrolyzer with an AC efficiency of 79% is used. Coupling efficiency between the wind turbine and the electrolyzer is assumed to be 96%. Annual energy production is given for a Great Plains US site with annual energy capture of 530 MWh/yr per 200 kW turbine. Water requirements are for electrolyzer feedwater.

[c] Land use for hydroelectric power varies greatly depending on the location. The range shown is for large projects in various countries. Water requirements are for electrolyzer feedwater only. Evaporative losses at the reservoir are likely to be much higher than feedwater requirements.

[d] It is assumed that biomass productivity of 10 dry tonnes/hectare/year is achieved, and that the biomass has a heating value of 20 GJ/dry tonne. The energy conversion efficiency of biomass to hydrogen via gasification in a Wright-Malta gasifier is assumed to be 72%. Water use is based on a rainfall of 30-70 cm per year needed to achieve a biomass productivity of 10 dry tonnes/hectare.

[e] This is the amount of land needed to produce enough hydrogen to fuel all US cars and light trucks at t 1987 driving levels assuming 1) The fleet average mileage on gasoline is raised to 34 mpg and 2) these more efficient cars are equipped with fuel cells.

Senator FORD. Thank you.
Dr. Prater.

STATEMENT OF DR. KEITH PRATER, ON BEHALF OF THE BALLARD POWER SYSTEMS, INC., NORTH VANCOUVER, BRITISH COLUMBIA, CANADA

Dr. PRATER. Thank you, Mr. Chairman.

In view of the time, I will limit my comments to the status of fuel cell technology and to demonstration programs which are under way, and to my perception of the importance of such demonstration programs at this point in time. The previous speakers have certainly indicated the importance of hydrogen as a fuel and addressing environmental and energy security issues, and they have also mentioned the importance of fuel cells.

Now, a fuel cell, as you are aware, is essentially a battery which has been designed to be continuously refuelable. That is, it is a continuous source of electrical power, rather than an intermittent source, as is a battery. But, like a battery, the fuel cell consists of a couple of electrodes and stuff in the middle called an electrolyte, which is completely analogous to the acid in your car battery.

A number of fuel cell technologies, particularly the phosphoric acid fuel cell technology, have been developed along those lines. That is, using a liquid as the electrolyte. Back in the 1960's, General Electric developed for NASA a fuel cell technology in which those liquid electrolytes were replaced by a piece of plastic, producing what was then called the SPE, or solid polymer electrolyte, now more generally called the proton exchange membrane fuel cell.

This is an extremely simple device. I have got one here. And it simply consists of a couple of electrodes and a piece of plastic between them. If you supply hydrogen to one side and oxygen to the other you make electricity and water. It is this that is the core of the fuel cell technology which Ballard in Vancouver, Canada, has been developing for a number of applications. But, in particular, 2 or 3 years ago we made a substantial improvement in this technology which resulted in a significant reduction in the size, weight, and ultimate cost of the technology, which makes it now feasible to use these fuel cells to power vehicles.

The other thing which Ballard has accomplished which was not present in the original technology is the operation of these fuel cells on air, rather than pure oxygen. Both of these are required for the ultimate commercialization of this technology. Now, Ballard is not in the business of doing research and development. Ballard is in the business of manufacturing and commercializing. And so we have taken this from the laboratory, built it into fuel cells which we are now manufacturing and have shipped to countries around the world for evaluation purposes. We have essentially converted this into a product.

We are now focusing on the demonstration and sale of these devices. And I underline demonstration, because we, as a company, find that demonstration is absolutely imperative to moving this technology along. Demonstration is required to overcome the risk aversion which is present in governments, in industries, and in the

general public in moving any new technology into commercialization.

We find that we not only have to demonstrate that this technology works and is safe, but we have to involve in those demonstrations our ultimate customers. And, as I will address in just a moment, we have done that in a bus demonstration program.

We also find that demonstrations provide us with firsthand opportunity to learn not only the strengths, but also the limitations of the technology. We see research, development, and demonstration not as a linear process, one following the other, but we see it as a cycle. One does demonstrations to learn what additional development and research must be done to ultimately reduce costs and bring the product to commercialization.

There is a risk associated with early demonstration of a technology, and we as a small company are well aware of that. Certainly, some of our demonstrations do not work the way we would like them to. But in the process we learn and we improve the product far more rapidly than we would if we simply stayed in the laboratory.

Let me turn now very briefly to one of the demonstration programs that is presently under way in the Province of British Columbia. We now have under way a program, which is funded at a level of 4.84 million Canadian dollars, about $3.8 million U.S. dollars, to within a 26-month period demonstrate the operation of a 30-foot transit bus, fully powered by our fuel cells, and operating on gaseous hydrogen stored on board the vehicle. That bus is to be operating by the end of 1992. The bus itself will be ordered within the next month and should be received by the end of this year.

We have taken an interesting approach to the development of this program. We have created a steering committee, which not only monitors the program, but which allocates and approves further funding as we go through the process. This committee is chaired by a representative of the local transit agency, which will in fact be testing this bus, a user. We also have users on board this steering committee from the U.K., potential users, and from the United States as well.

The original plan for this program was that phase I, the program which has been funded, is to be a feasibility demonstration that one could in fact operate a bus on solid polymer fuel cells, PEM fuel cells, and on gaseous hydrogen on board. Phase II of the program was seen as a program in which methanol would be the on-board fuel, involving on board the bus a reformer, which converts the methanol into a hydrogen-rich gas stream.

In discussions with the potential users, the B.C. Transit Authority and people from London and from California, we have received a very, very strong impression that they would prefer to have hydrogen as the on-board fuel. And their argument is that to do so substantially reduces the maintenance cost associated with operating such a bus. They would rather have a single natural gas or methanol reformer at the depot, rather than a reformer on each bus. Now, this again is input from the potential users, sir.

I would like very briefly to point out and to elaborate a bit on Dr. Ogden's comments about the potential for automobiles. We are aware of a study conducted by Directed Technologies, Incorporated,

which supports the position of Dr. Ogden that a fuel cell powered vehicle can in fact be made and it can be operated economically on technology which is available today.

We are also aware of a program under way by Energy Partners in Florida to demonstrate such a vehicle, again, based on technology which is present today.

I would summarize my comments by pointing out that in order for new technologies to be accepted there must be leadership from governments and, in particular, there must be leadership from leading governments, such as the United States. With regard to why there should be programs and, in particular, demonstration programs today, I would point out that the technology is ready. It is not commercial. It is not economic. But it is ready. We are not in a position where we were in 1960, when President Kennedy said we were going to the moon and we had to develop the wherewithal to accomplish that. We have the technology today to demonstrate vehicles operated on hydrogen and powered by fuel cells.

Other countries are in fact moving ahead. There is no question. Germany, Japan, and even Canada have substantial programs in this area. And, as Senator Harkin mentioned, the Province of British Columbia, with its 3 million people, is moving ahead, in particular, supporting this bus program to the tune of $3.8 million.

I would encourage the United States to move more rapidly than it has been in hydrogen demonstrations. We in Canada feel that if such actions are not taken in the next century we in North America would be buying our energy and our transportation technology offshore.

Thank you very much, sir.

[The prepared statement of Dr. Prater follows:]

PREPARED STATEMENT OF DR. KEITH PRATER, ON BEHALF OF THE BALLARD POWER SYSTEMS, INC., NORTH VANCOUVER, BRITISH COLUMBIA, CANADA

INTRODUCTION

A nation's choice of energy systems impacts its economic and political security, and the health and well being of its citizens. In the case of leading nations, such as the United States, the choice of energy systems may affect the survivability of mankind on Earth.

It is clear that our present world energy system cannot be sustained indefinitely. Whether due to limitations in the availability of fossil fuels or due to limitations in the ability of the environment to absorb the byproducts of our present energy system, mankind is approaching the day when the present energy system will be unacceptable. It must be the responsibility of governments to assure that appropriate alternatives are available and instituted before a crisis is reached.

The Bill being deliberated by this subcommittee addresses one important aspect of the development, demonstration, and implementation of an improved, sustainable energy supply and use system. Ballard Power Systems supports the concept and method set out in this Bill. Our testimony will address: (1) the importance of hydrogen as an energy vector in any sustainable energy system; (2) the importance of fuel cell technology in any environmentally acceptable energy use system; (3) the importance of research, development, and demonstration programs in the creation and implementation of new energy technologies; and (4) the appropriateness today of development and demonstration programs for hydrogen production and use technologies.

THE PROBLEMS

As the human population of Earth continues to expand and as the expectations of that population for material goods and for services increase, the consumption of energy in its various forms continues to grow. The most concentrated forms of

energy available today—uranium and other fissionable materials; petroleum; coal; and natural gas—are fossil fuels with two unfortunate attributes. They are limited resources and their use generates byproducts which may ultimately endanger the survival of humankind.

In the last two decades, we have been faced with the threats of: economic disaster due to disruptions in the supply of petroleum; death and the widespread contamination of people and property, resulting from to a nuclear accident; serious health and economic damage, caused by localized air and water pollution; and, now, the potential of worldwide climatic changes, due to our discharge of the gaseous byproducts of our civilization into the atmosphere. These threats to our collective health and security have prompted a growing call for energy systems and energy conversion devices which allow for some measure of population and economic growth while limiting and even reversing the negative environmental impact of our present energy use systems.

Most of our difficulties associated with energy use are due to the fact that our energy systems are based largely upon the use of hydrocarbon fuels in heat engines. These engines are mechanical devices, like the internal combustion engine, with inherent frictional as well as theoretical limits to the fraction of the energy originally present in the fuel which can be converted into useful work. The typical automobile operating in the city expels about 85% of the energy in the fuel it consumes into the environment as useless heat. And, because heat engines require that the fuel be burned to produce heat, the process invariable produces waste gases, such as carbon dioxide, oxides of nitrogen, and unburned hydrocarbons, which pollute our atmosphere.

THE SOLUTIONS

The ultimate solution to these problems is an energy system in which the harvesting of energy, its transportation and ultimate use cause negligible environmental damage. At the same time energy must be available in quantities and forms which allow for the maintenance of the economic well being of our people and the political and economic security of our nations.

Hydrogen, produced from renewable energy sources, is the only energy vector which can be produced and used with negligible environmental damage. Its production from energy and water and its reconversion in a fuel cell to water and energy is a cycle which can be repeated indefinitely without the production of environmentally damaging byproducts. Hydrogen also has the strategic advantage that it can be produced from readily available fossil fuels, such as natural gas, during a transition period to provide environmental benefits during such a transition to renewable energy sources.

The fuel cell is a key component of this ideal energy system. A fuel cell is an electrochemical energy conversion device, like a battery, which transforms the energy in a fuel directly into electricity, without combustion. As a result, a fuel cell is more energy efficient than heat engines and produces none of the byproducts which arise from the combustion process in heat engines. In particular, when hydrogen is used as the fuel, a fuel cell produces only electrical power, usable heat, and pure, drinkable water.

A fuel cell has advantages over batteries in that, unlike a battery, a fuel cell is a continuous source of electrical power. Thus, a fuel cell can be used as a source of continuous, primary electrical power in an electric utility application. A fuel cell can also power a vehicle. Such a vehicle could be refueled in minutes, like a gasoline-fuelled automobile, rather than requiring hours, as is the case with battery-powered electric vehicles.

THE STATUS OF THE TECHNOLOGIES

An energy system based upon hydrogen will include hydrogen production technologies, hydrogen storage and transportation technologies, and hydrogen use technologies. Others are better qualified to discuss the details of hydrogen production, storage, and transportation, and only brief mention of these will be made. The bulk of this section will deal with the status of fuel cell and supporting technologies.

Hydrogen Production

A variety of hydrogen production technologies have been and are being developed and commercialized. Hydrogen is routinely produced in large quantities by the steam reforming of methane and other light hydrocarbons in natural gas. This process produces carbon dioxide as a byproduct, but for fixed site installations, the collection and sequestering of the carbon dioxide is feasible. This is the likely technology for the production of fuel hydrogen during a transition period, until processes

based upon renewable energy sources become established. Directed Technologies Inc. has calculated that the wholesale cost of hydrogen to be consumed in an automobile powered by a fuel cell would cost between $0.25 and $0.55 per gallon of gasoline equivalent when burned in a similar vehicle. That is comparable in cost to gasoline derived from $15/bbl oil.

Hydrogen can also be obtained from the steam reforming of methanol. Methanol, which is typically produced from methane derived from natural gas, is a conveniently transportable liquid. It is also more easily steam reformed than is natural gas. For these reasons, methanol has been identified as a likely fuel for fuel cell powered vehicles. While large stationary methanol reformers are commercially available, a small, light, load-following methanol reformer suitable for vehicular applications is not commercially available. Development and demonstration programs for such a reformer are under way in Europe, Japan, Canada and in the United States.

Hydrogen is also produced commercially by the electrolysis of water. Several technologies are available for this purpose and others are being developed. Electrolysis is an efficient process, with energy efficiencies of commercial units in the range of 85%, and developmental units in excess of 90%. Electrolysis can, of course, be easily linked to such renewable energy sources as solar, wind, hydraulic, and, ultimately perhaps, nuclear fusion. The present disadvantages faced by electrolys is technology are its relatively high capital cost and, in most areas of the world, high electricity costs. In such countries as Canada, with extensive hydroelectric potential, electrolysers are being installed for the production and export of hydrogen.

Many other technologies are being evaluated as potential methods of producing hydrogen. These include thermal water dissociation cycles, photoelectrochemical water splitting, and the exploitation of various biological systems. In the longer term, these may offer less expensive options to the present technology.

Hydrogen Storage and Transportation

Hydrogen transportation and storage are, for some applications, well known technology. Hydrogen, either as a pressurized gas or as a liquid is commonly transported by truck and rail. Hydrogen pipelines hundreds of miles in length have operated in Europe for decades. In fact, hydrogen was supplied to most households in Europe until the middle of this century in the form of "Town Gas". It is true that "hydrogen embrittlement" of metals must be considered in creating a transportation system, but this is an issue which is dealt with successfully today.

The greatest issue for hydrogen storage and transportation is the low volumetric energy density of hydrogen, whether stored as a gas or a liquid. This becomes an issue for volume-sensitive applications, such as the automobile. Hydrogen gas, stored at 5000 psi, occupies about ten times the volume of gasoline with the same energy content. Due to the higher efficiency of the fuel cell over combustion engines, a fuel cell powered automobile will require a substantially smaller hydrogen fuel tank than an equivalent hydrogen-fuel led internal combustion engine (ICE) automobile.

In a study, entitled "White Paper on Economically Competitive Fuel Cell/Electric Propulsion for Automobiles", Ira F. Kuhn, Jr. of Directed Technologies, Inc. in Arlington, Virginia, has concluded that equivalent performance and range to that obtained from a standard gasoline powered ICE automobile can be obtained when the same vehicle powered by a fuel cell and fuelled with gaseous hydrogen stored in commercially available cylinders. This study also concludes that the hydrogen/fuel cell automobile would weigh essentially the same as the gasoline powered automobile.

Safety is a concern with any energy storage system and particularly in transportation applications. A number of studies have suggested that, due to its buoyancy and high volatility, hydrogen would be a safer transportation fuel than gasoline. Certainly the existing DOT safety requirements for gas cylinders are substantially more rigorous than those for gasoline tanks.

While improvements in hydrogen storage technologies are desirable for the ultimate commercialization of a hydrogen fuelled vehicle, the demonstration of such a vehicle is possible today, based upon existing technology. This has been made possible largely by significant improvements in fuel cell technology, first demonstrated by Ballard Power Systems.

Fuel Cell Technology

In this section, we first describe the design and operation of a fuel cell, for those unfamiliar with this technology. We then describe the Ballard Solid Polymer Fuel Cell (of more generically the Proton Exchange Membrane [PEM] fuel cell). Finally, we discuss the improvements in this technology which have made the fuel cell powered vehicle practical and the present and near-term state of the technology.

A generalized fuel cell is shown in Figure 1. It consists of two porous electrodes at which the energy conversion process takes place. A fuel (hydrogen, in the case of the example) is supplied to one electrode while an oxidant, usually oxygen from the air, is supplied to the other electrode. At the fuel electrode (the anode) the fuel molecules give up electrons to the electrode and create an electric current in the wire leading from the fuel electrode through the electrical load to the oxidant electrode (the cathode). The remnants of the fuel molecules are now positively charged ions—hydrogen ions in the example shown in Figure 1.

The intrinsic tendency for the fuel and oxygen to react, as demonstrated by normal combustion, is manifested as a voltage between electrodes of the fuel cell. When the electrons, drawn by that voltage, arrive at the oxidant electrode, they are removed from the electrode by oxygen molecules, producing negatively charged oxygen ions. The build-up of positive ions at the anode and negative ions at the cathode would soon stop this process if there were no mechanism for these charges to be dissipated. There must, therefore, be an "electrolyte" between the two electrodes to allow the migration of ions from one electrode to the other.

In the example in Figure 1, the electrolyte allows the positively charged hydrogen ions to migrate from the anode to the cathode where they react with the negative oxygen ions to produce the product of this reaction, water. In this example, the electrolyte is an acid, completely analogous to the acid electrolyte in the automotive battery.

A number of fuel cell types have been developed. These differ principally in the material chosen as the electrolyte. The Phosphoric Acid Fuel Cell uses liquid phosphoric acid as the electrolyte. This system has been developed to the semi-commercial stage, in that International Fuel Cells in the U.S. and several Japanese companies are offering 200 kW fuel cell systems for stationary co-generation demonstrations. An 11 MW system has been installed at a utility in Japan.

The U.S. space program utilizes fuel cells incorporating an aqueous alkaline electrolyte. This is a relatively specialized fuel cell system which requires special treatment of fuel and air supplies to remove carbon dioxide. This may limit the applicability of this system for terrestrial applications.

Two high temperature fuel cell systems, the Solid Oxide Fuel Cell and the Molten Carbonate Fuel Cell, are being developed principally for large stationary utility applications. These fuel cells operate at between 650 and 1000 C and may, ultimately, operate directly on hydrocarbon fuels.

None of these fuel cell systems offer significant potential as power sources for vehicular applications. They are too large, or too heavy, or too complex, require unacceptable warm-up times, or require special systems which are incompatible with the vehicular application. It was not until Ballard Power Systems demonstrated significant improvement in the performance of a fuel cell utilizing a polymeric electrolyte that a practical fuel cell powered automobile became possible.

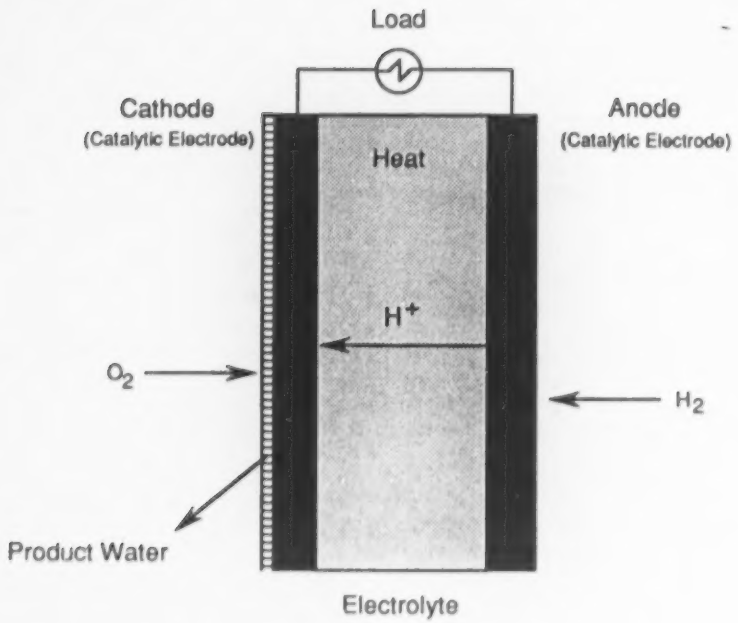
The Ballard Solid Polymer Fuel Cell (SPFC) (or generically the PEM fuel cell) uses as its electrolyte a polymer membrane which looks rather like a thick sheet of food wrap and can be handled easily and safely. This membrane is an electronic insulator, but an excellent conductor of hydrogen ions. The materials used to date consist of a fluorocarbon polymer backbone, similar to Teflon, to which are attached sulfonic acid groups. The acid molecules are fixed to the polymer and cannot "leak" out, but the protons on these acid groups are free to migrate through the membrane.

The anode and cathode are prepared by applying a small amount of platinum black to one surface of a thin sheet of porous, graphitized paper which has previously been wet-proofed with Teflon. The electrolyte is then sandwiched between the anode and cathode, and the three components are sealed together under heat and pressure to produce a single "membrane/electrode assembly" (MEA). This assembly, which is the heart of the fuel cell, is less than a millimeter thick.

The anode and cathode are contacted on the back side by flow field plates made of graphite in which channels have been formed. The ridges between the channels make electrical contact with the backs of the electrodes and conduct the current to the external circuit. The channels supply fuel to the anode and oxidant to the cathode.

Water is produced at the cathode during power generation. Due to the hydrophobic nature of the Teflon treated carbon paper cathode support, the water is rejected from the back of the support into the oxidant gas stream. As the SPFC operates at about 80°C, the water is produced as liquid water and is carried out of the fuel cell by excess oxidant flow.

A single fuel cell produces about 0.7 V. For applications requiring higher voltages, several cells are combined together in a fuel cell stack. Figure 2 shows Ballard's



Generalized Fuel Cell

Figure 1

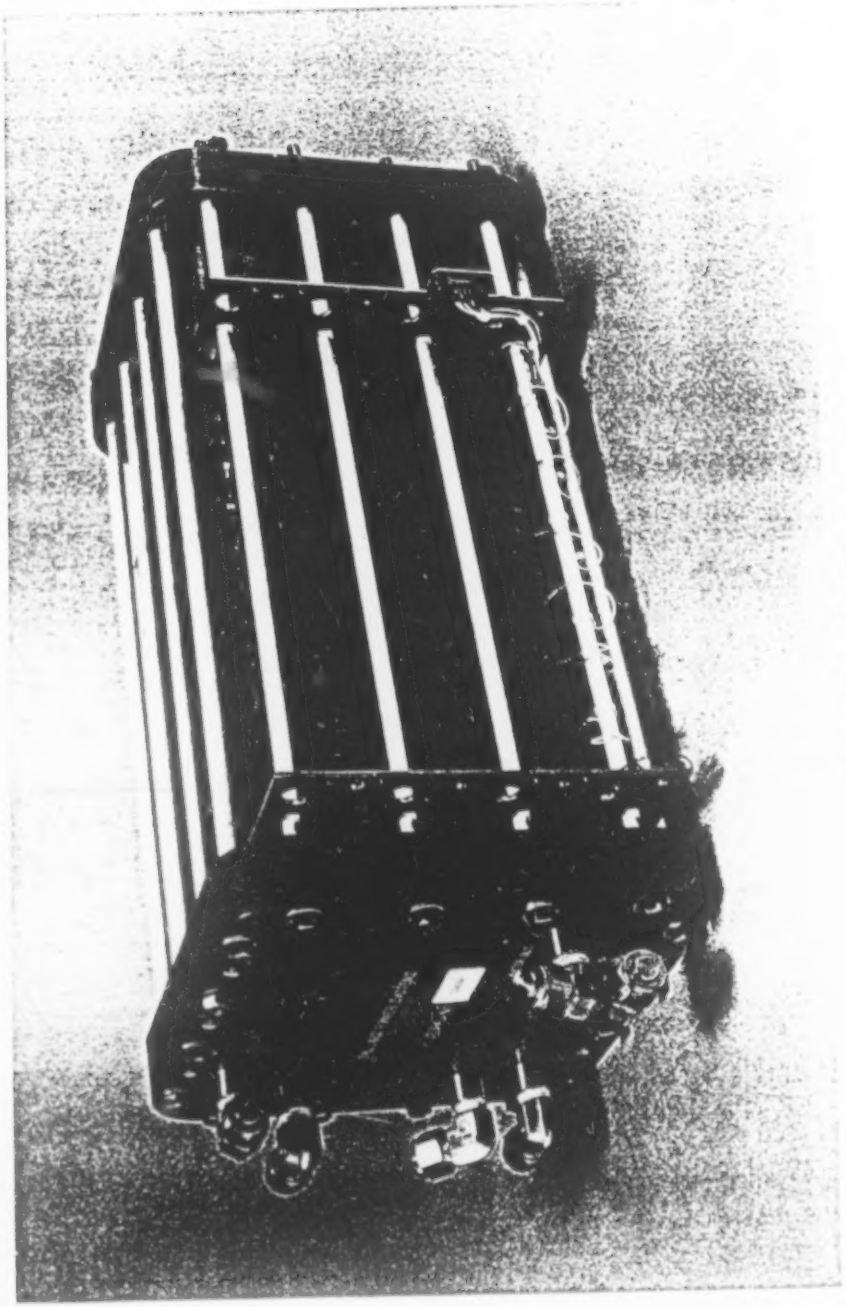
standard 35-cell stack which delivers nominally 24 V dc. When supplied with hydrogen as the fuel and with air as the oxidant, this unit will provide over 5 kW of power. If oxygen is supplied as the oxidant, the unit will provide over 10 kW of power. The present commercial unit, as shown in Figure 2, weighs just under 100 lbs (45 kg) and occupies a space of 10" x 10" x 22" (25 cm x 25 cm x 56 cm). Substantial size and weight reductions are now being made in this unit. But even in its present form, this fuel cell can power a bus, as will be described later.

Just as the engine block in a automobile requires ancillary systems, such as a fuel system, a cooling system, and a control system, the fuel cell stack also requires ancillaries. Ballard has introduced the first complete SPFC power system. A picture of this unit is shown in Figure 3. The Ballard Power Generator System (PGS) requires pressurized hydrogen and pressurized air for operation and produces unregulated dc power. The PGS contains a gas metering system, a cooling system, a water management system, a fuel cell stack, and a monitoring and control system. The latter system provides single-button start-up and shut-down as well safety monitoring. These systems are being evaluated my major companies in Japan, England, Switzerland, and Italy.

Ballard has also demonstrated a complete power system operating on methanol as the fuel. The system contains a methanol reformer to supply the hydrogen, a compressor to supply air, a fuel cell stack, a thermal and water management system, and a control system. This represents the first such complete hydrocarbon fuel cell system for the Solid Polymer Fuel Cell. Programs have been proposed to the Canadi-

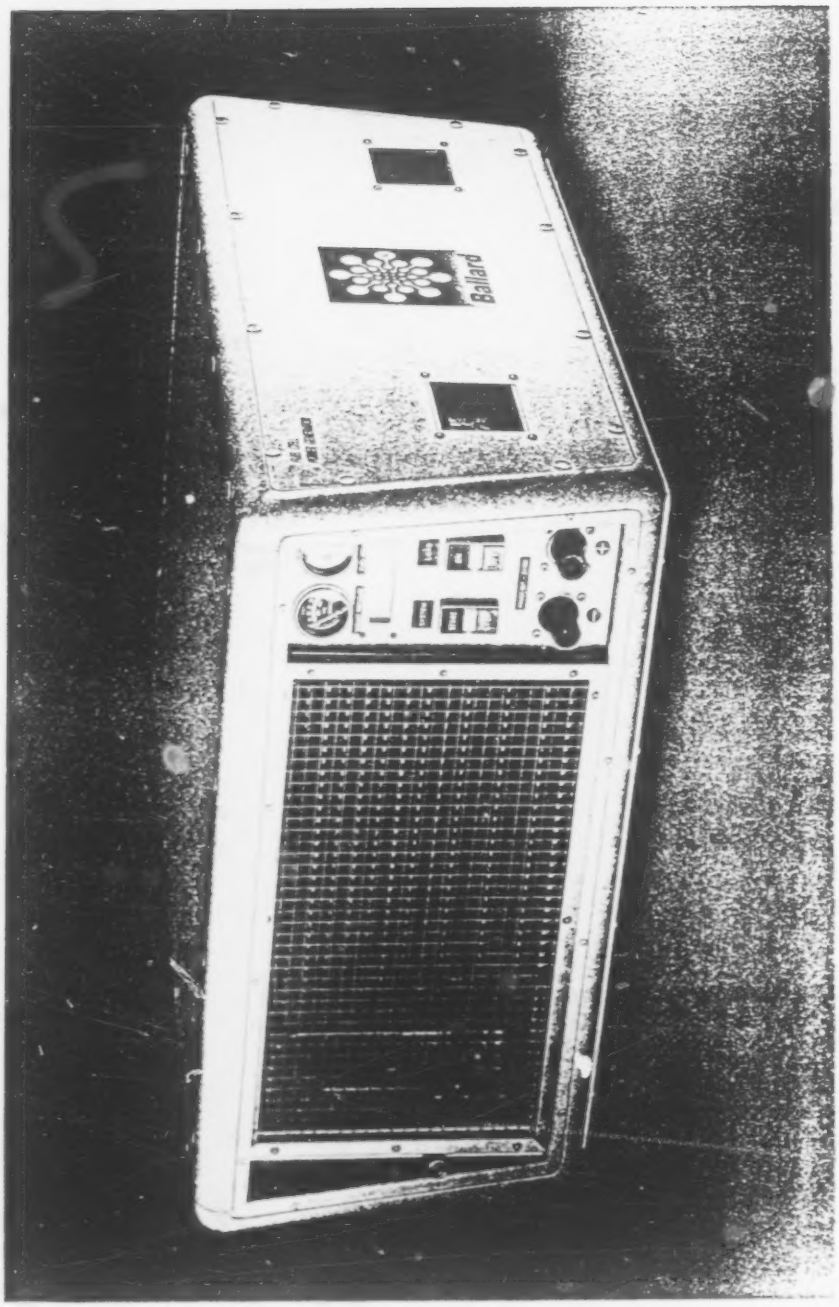
an and British Columbia governments to extend this system to operate on natural gas and to demonstrate its use in utility applications.

In summary, Ballard has demonstrated that the Solid Polymer Fuel Cell can be made small enough and light enough for vehicular applications. The low temperature of operation for this system means that minimal warm-up time is required for full power operation. The system contains no corrosive or toxic liquids and is thus intrinsically safe to manufacture and maintain and presents no disposal issues. The system is intrinsically reliable. It is reasonable to expect that the fuel cell stack would require no maintenance during the life of an automobile. Finally, it is possible to project system costs in the range of $100/kW for an installed fuel cell engine. This would represent an acceptable cost for the personal automobile.



Ballard Fuel Cell Stack

Figure 2



Ballard Power Generator System

Figure 3

THE CHALLENGES

Today, examples are available of all the technologies necessary to demonstrate a hydrogen based energy system. No new technologies must be created for such a demonstration. That is not to say that there are no challenges left for the establishment of a commercial system based upon hydrogen as the major energy vector.

Any new technology system which attempts to replace an established technology will be more expensive until economies of scale and the maturing of the new technology system reduce costs. But until new technologies have been demonstrated to be feasible in real applications, major commercial investment in cost reduction, in better supporting technology, and in the acquisition and installation of the new technology will not take place.

The major challenge today, then, is to demonstrate the existing technologies. In the process, limitations will be identified and opportunities for improvement will be discovered. More importantly, the intrinsic risk aversion of governments, companies, and individuals when faced with accepting new technologies will begin to be assuaged. These are critically important steps in reducing the cost of hydrogen energy technologies, in introducing these technologies into our energy system, and in solving our environmental problems.

Demonstration Programs Proposed and Under Way

There are a number of programs presently under way focused on the demonstration of various components of a hydrogen-based energy system. Very few of these programs are taking place in the U.S. The following discussion is not intended to be comprehensive, but, instead, to be illustrative.

In the areas of hydrogen production, we are aware of three major programs in various stages of development. Germany is involved in a program to establish a very large photovoltaic/electrolysis system in Saudi Arabia. Hydrogen produced in Saudi Arabia would be pipelined or shipped to Germany as a clean source of energy. The initial feasibility demonstration phase has been completed and is generating hydrogen in Saudi Arabia.

Canada presently has three electrolytic liquid hydrogen plants in operation, with a combined production of 45 ton/day. Two of these are in Quebec and the third is in Ontario. Much of this liquid hydrogen is now exported to the U.S.

Quebec and the European Economic Community have just completed a $4.2 million feasibility study for a program to produce, liquefy, and ship 45 ton/day of liquid hydrogen from Quebec to Europe. The shipment would be by sea in specially designed 200 ton barges. The liquid hydrogen would be delivered to Germany at Hamburg and to Italy. Initially, the hydrogen delivered to Hamburg will be used to power a fleet of 400 buses. The next phase of this program is an engineering design phase expected to cost between $50 million and $75 million. The province of Manitoba is discussing a similar project with the Japanese.

In the areas of hydrogen applications, Daimler Benz has over the years demonstrated a number of hydrogen fuel led internal combustion engine vehicles as well as metal hydride technology for hydrogen storage. Stimulated by plans for a fleet of 400 hydrogen fuelled buses for Hamburg, Daimler Benz is actively developing commercial designs for such buses.

Ballard is presently working on a program to demonstrate the operation of a 30 ft transit bus fully powered by a 120 kW Ballard fuel cell system and fuelled by compressed hydrogen gas. The bus, which is to be operational by the end of 1992, will be ordered within the next month from a California manufacturer. A picture of such a bus is shown in Figure 4. The proposed layout of the fuel cell, hydrogen tanks, and other systems is shown in Figure 5.

This CAN $4.84 million (U.S. $3.76 million), 26 month Phase 1 program has been funded to the extent of CAN $3.84 million (U.S. $3.00 million) by the province of British Columbia and CAN $1.00 million (U.S. $0.76 million) by the Canadian Government. The program is being guided by an international steering committee including potential users from the UK and the U.S.

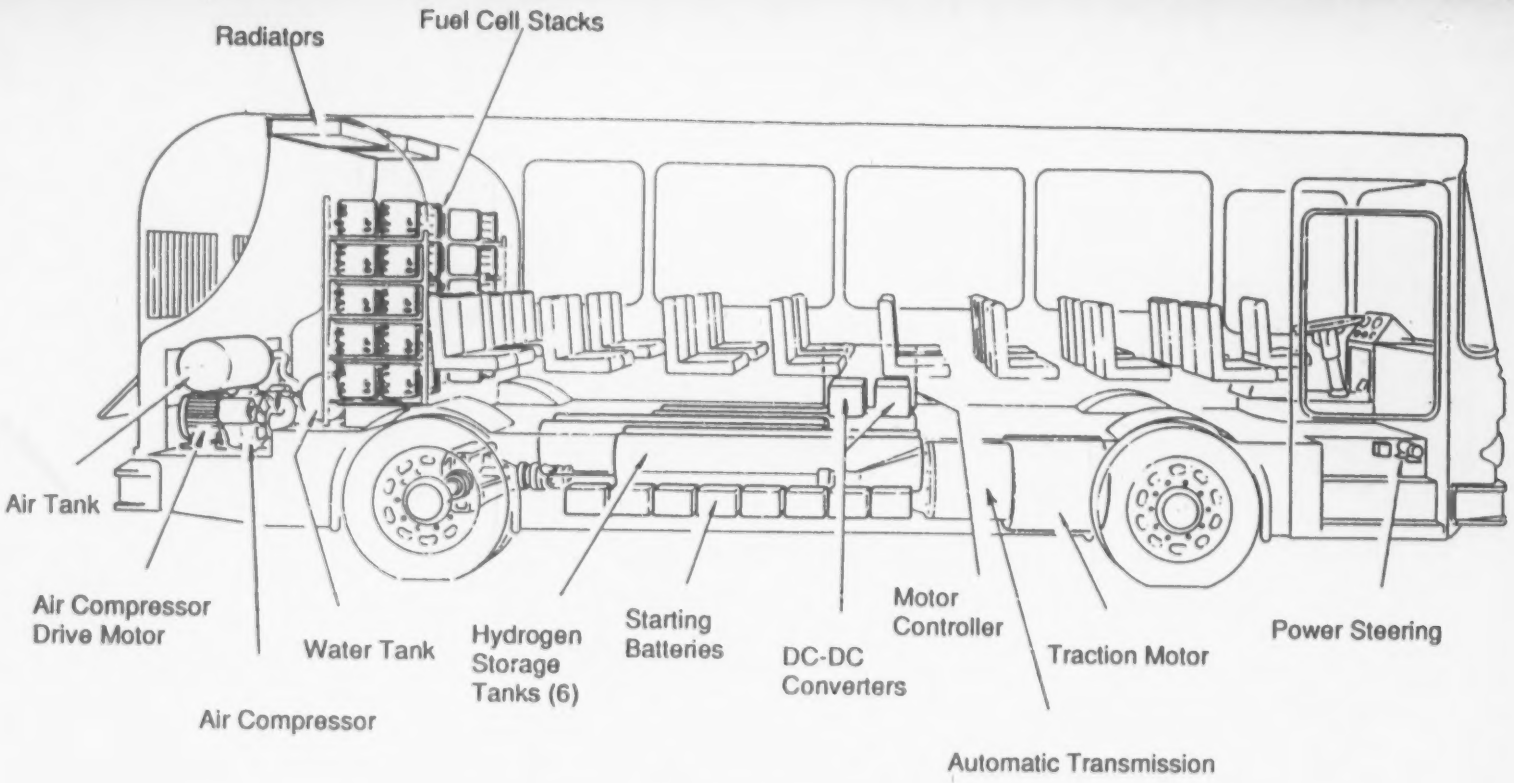
Phase 1 is seen as the feasibility demonstration phase of a multi-phase program to create a commercial bus within a five year time frame. The specific objective of this first phase is to demonstrate a bus fuel led by hydrogen and powered entirely by fuel cells which provides driver acceptable performance. Some specific performance requirements are presented in Figure 6.

The second phase of this program is to begin January 1993. The specific objectives of that phase will be defined by a group, including potential users, in mid-1992. Potential suppliers and users of the ultimate commercial bus are expected to share in the funding of Phase 2. Originally, Phase 2 was to include the demonstration of either methanol or natural gas as the on-board fuel with the incorporation of a re-

former into the bus power system. Recent discussions with potential users have indicated a strong desire to use hydrogen as the fuel on-board the bus to eliminate the maintenance issues associated with an on-board reformer. Such a system also offers the possibility of collecting carbon dioxide produced by a stationary reformer at the bus depot. Carbon dioxide produced from reformers on the buses could not be captured and would have to be vented to the atmosphere. Phase 2 is now likely to include the demonstration of improved hydrogen storage technologies.

Proposed Fuel Cell Bus

Figure 4



Fuel Cell Powered Transit Bus

Figure 5

PERFORMANCE REQUIREMENTS
DRIVING DESIGN OF PROPULSION SYSTEM

	Requirements (all with full seated passenger load)
Gradability	30 kph on 8% Grade
Acceleration	1 - 50 kph in 20 seconds
	Accelerate to and maintain 70 kph on level road
Start	No overnight recharging allowed. System must recharge on-board batteries.
	Start on 20% Grade
Gross Weight	9752 kg (21,500 lbs)

Figure 6

The U.S. DOE is presently funding two programs which make a limited contribution to the demonstration of hydrogen energy systems for transportation. In the so-called "Georgetown Bus" program, DOE is funding the demonstration of a fuel cell powered bus, based upon phosphoric acid fuel cell, technology using methanol as the fuel with an on-board reformer.

In another DOE program, General Motors has been contracted to demonstrate a Solid Polymer Fuel Cell system incorporating a methanol reformer. Ballard is a subcontractor to GM for this $13.8 million first phase of a program designed to demonstrate a methanol fuelled, fuel cell powered prototype automobile in five years.

On a more aggressive time table, Energy Partners Inc. of West Palm Beach, Florida has announced plans to demonstrate a hydrogen fuelled, fuel cell powered automobile by March 1992. The vehicle, which is in place, incorporates advanced composits for light weight. It will be powered by a 40 kW battery/fuel cell hybrid power system.

In a more general context, Canada is considering a proposed CAN $100 million five year hydrogen research, development, and demonstration program as part of its environmental plan. Even more impressive, the province of British Columbia, with a population of some 3 million, is planning a CAN $100 million five year program for hydrogen technology development and demonstration. A Hydrogen Systems Agency has been established, an Executive Director has been selected, and an operating budget for the next five years has been approved. The CAN $3.84 million committed to the fuel cell bus demonstration project is a part of this program.

THE PROPOSED PROGRAM

The program proposed in S. 1269 would represent a major step in the development and demonstration of hydrogen-based energy system technologies. As such, it would begin to bring the U.S. in line with programs which are well under way in Europe, Japan, and Canada.

It is our view that the technologies are in place to support the demonstration programs envisioned in this Bill and that such demonstrations are vital to the further development and ultimate commercialization of these technologies. Without a program such as the one proposed in S. 1269 and the commitments of federal, state, and local governments to the enactment of environmental protection legislation which will further stimulate the adoption of hydrogen energy technologies, these technologies will not be in place before an environmental crisis causes severe economic and health disruptions.

Senator FORD. Thank you.

Dr. Serfass.

STATEMENT OF JEFFREY A. SERFASS, PRESIDENT, NATIONAL HYDROGEN ASSOCIATION

Mr. SERFASS. Thank you, Mr. Chairman.

Good morning. This morning I am speaking to you on behalf of the National Hydrogen Association, of which I am the president. We are a relatively new organization, about 2 years old. We have approximately 30 members. We view ourselves principally as representatives of industries interested in hydrogen. We do have a significant portion of our membership from both small and large industrial organizations. But we also represent university and research organizations and their interests in hydrogen as well.

I certainly would like to begin by applauding the efforts of Senator Harkin, who has certainly joined the growing ranks of those on Capitol Hill who recognize the tremendous benefits of hydrogen-related technologies.

I would like to speak briefly on our view of the relationship of this bill to the Matsunaga Hydrogen Research and Development Act recently signed into law by President Bush. Clearly, industry feels that we need a transition strategy. In fact, those words are part of our mission statement. We feel the need to develop the strategy in which hydrogen plays a transition role from today's

energy resources to the time when renewable energy resources will play a more important role in our energy systems.

In order to accomplish that kind of a mission, we need the specificity in goals and the specificity in the management plan and the research program that this bill provides. The Matsunaga Hydrogen Research and Development Act provides an excellent structure for development of a national hydrogen program. This bill takes that a step further and provides the technologies, the applications, and the interest in demonstrations that is necessary to continue to advance the role of hydrogen and advance the U.S. program.

The applications that are particularly of interest to our organization are recognized by this bill, clearly. I think and our organization feels, as a result of a study principally sponsored by NASA with our organization that vehicles provide the best near-term opportunity. That is where the fuel is valued the highest in our use of it, and our studies show that if you can produce renewable hydrogen at $25 a million Btu that you can compete with today's cost of gasoline, with the developed fuel cell technology that Dr. Prater and others are working on, and with the storage systems that this bill identifies are necessary in such a vehicle.

Though not mentioned specifically by this bill, the second application of interest to our group is certainly aircraft. NASP, the National Aerospace Plane Program requires hydrogen because of the high altitude and speeds of which it will be flying. But, in the end, commercial aircraft may well benefit by developed hydrogen technologies.

Third, the electric role in hydrogen that Dr. Birk will be speaking about later is important to our organization as well. Potentially, electric and gas utilities provide the infrastructure necessary to deliver hydrogen as a commodity and to use hydrogen in electric generation and storage systems as well.

The key to any hydrogen system just about is fuel cells. As Dr. Prater mentioned, fuel cells are the link between the fuel and the application, the electric generation in the case of utilities, propulsion in the case of vehicles. We need a transition that gets us from today's fossil energy resources to renewable energy resources. Hydrogen can provide that transition. Like electricity, it is a carrier. Today we can use fossil resources. Tomorrow we can use renewable resources to provide the environmentally acceptable energy systems that we require.

Therefore, the National Hydrogen Association clearly supports this bill. It takes us a step further in providing the guidelines for the Department of Energy and what they should deliver in the form of a plan, what they should deliver in the form of a program, and the demonstration or ventures that should be considered.

We would also like to send a clear message to Congress by saying that industry is not only interested in hydrogen, but has a tremendous amount of capability in the variety of hydrogen related technologies addressed by this bill. But industry is not long-term oriented enough to go it alone. We require the Federal support and State agencies to bring these technologies to the marketplace, and we need the help of the Federal Government.

This bill, S. 1269, provides that kind of assistance.

Thank you.

[The prepared statement of Mr. Serfass follows:]

PREPARED STATEMENT OF JEFFREY A. SERFASS, PRESIDENT, NATIONAL HYDROGEN ASSOCIATION

Good morning, my name is Jeff Serfass. This morning I am speaking as President of the National Hydrogen Association (NHA). On behalf of the NHA, I would like to thank Chairman Ford and the Subcommittee staff for the opportunity to appear in support of S. 1269, "The Renewable Hydrogen Energy Research and Development Act."

The NHA applauds the efforts of Senator Harkin for his willingness to join the ranks of those on Capitol Hill who recognize the tremendous benefits of hydrogen-related technologies.

I am here to provide industry's view of S. 1269 and its impact on reaching the long term goal of hydrogen as an environmentally superior energy carrier and fuel. Hydrogen has the potential to flexibly provide one of the best linkages from a broad base of domestic fuel resources and renewable resources, to energy efficient, environmentally acceptable applications. Government and industry need a transition strategy for hydrogen—one that is realistic, yet promises to be effective—to develop and demonstrate appropriate technologies capable of meeting our energy requirements. To that end, I am pleased to be able to provide brief comments on our interest in S. 1269, and to relate this bill to the "Spark Matsunaga Hydrogen Research and Development Act," that was signed into law by President Bush in November of 1990.

The National Hydrogen Association's mission is to foster the development of hydrogen technologies and their utilization in industrial and commercial applications and promote the transition role of hydrogen in the energy field.

The National Hydrogen Association:

- promotes the long-term development of hydrogen production and utilization technologies;
- promotes the development and expansion of practical near-term applications for hydrogen;
- recognizes terrestrial and air transportation as two of the very important "near-term" applications for hydrogen fuel; and
- recognizes the environmental advantages of hydrogen fuel and the need to make it affordable to a mass market in a safe and efficient manner.

These items are recognized by industry as important to developing the potential of hydrogen. These items are key components of S. 1269. Therefore, we would like to see a recommendation from your Subcommittee that this bill move forward to the full Committee.

A HYDROGEN BILL COMPARISON

The hydrogen bill that has now become the Spark Matsunaga Hydrogen Research and Development Act was first introduced into the Senate in 1981. Almost ten years later, it was signed into law. Ten years, Mr. Chairman. Much credit should be given to the late Senator Matsunaga of Hawaii for his perseverance in the legislative process and his commitment to hydrogen for staying with it so long. The hydrogen bill written by Senator Harkin carries further what Senator Matsunaga started.

Comparing Section 5 of Senator Harkin's bill with Section 104 of Senator Matsunaga's bill—both are research and development sections—Senator Matsunaga's bill sets up the framework for a broad hydrogen program within the Department of Energy. Senator Harkin's bill provides specificity in two key areas:

- The design, building and testing requirements for specific technical areas (Sec. 5(a)).
- The specific requirements for the multi-year plan in Sec. 5(b).

In addition, this legislation adds specific requirements for demonstrations as part of Sec. 6.

We endorse these added program requirements because they will provide the stimulus to researchers to produce, industry to compete, and technology users to reconsider long-term plans. At the National Hydrogen Association, we feel that the projects identified in this bill are the right ones.

Since we can't predict exactly where technical and market successes will be achieved, all promising applications should be demonstrated—utilities, transportation, and infrastructure, including storage and transportation. In Section 5 of S. 1269, all three of these areas are addressed.

In comparing the requirements for hydrogen plans in both bills (Section 103 of the Matsunaga Act and Subsections 1 and 2 of the Harkin Bill), both bills utilize the

expertise of other government agencies and private sector individuals in the hydrogen area to consult with the Secretary of Energy in developing such a plan. From an industry perspective, we welcome the opportunity to help ensure that public R&D funds directly address the most promising and most important long-term opportunities—opportunities that are too distant for the private sector to support alone but, nevertheless, offer significant returns for the public welfare.

The main differences in the plans required by these two pieces of legislation is, again, one of focus. Within the five-year requirement for the Matsunaga Act Management Plan, S. 1269 develops the structure by siting specific areas to be included. The NHA's point of view is that these two pieces of legislation complement one another and will be seen that way by this Committee and by the Appropriations Committee.

For all of its benign environmental properties, hydrogen's terrestrial applications are, by and large, unproven on any realistic scale in the United States. Assessing priorities for hydrogen research, as called for in the Matsunaga Act, may prove elusive without the opportunity for tests and proof-of-concept demonstrations. From an industry perspective, S. 1269 is "on target" with the technologies listed Section 5.

We do think that the 30 year requirement for manufacturing, production and cost projections called for in S. 1269 is too long. We think a shorter time frame—perhaps 15 or 20 years—would be more realistic.

We applaud the efforts of Senator Harkin for drafting Section 6 of S. 1269 which promotes joint venture projects for renewably produced hydrogen. We would like to see "proof-of-concept" demonstrations as well as pilot plant demonstrations qualify under this section of the bill, perhaps in report language from the Committee. The reason for this view is that "proof-of-concept" demonstrations may be more appropriate and less risky at early stages of technology development.

On behalf of the members of the NHA, let me send a clear message to Congress: There is a great amount of industry capability and interest in hydrogen-related technologies. Industry is committed to working with federal and state government agencies to develop and bring them to the marketplace. In order for industry and academic research organizations to develop these technologies, we do need the help of the Federal Government. The position of the NHA is that S. 1269 provides such help.

Thank you for your patience and attention. I will be happy to answer any questions or to supply additional information for the record.

Senator FORD. Thank you very much.

Dr. Birk.

STATEMENT OF DR. JAMES R. BIRK, DIRECTOR, STORAGE AND RENEWABLES DEPARTMENT, ELECTRIC POWER RESEARCH INSTITUTE, PALO ALTO, CA

Dr. BIRK. I would like to just summarize the key points that I made in the written testimony, and really the three conclusions that I tried to achieve there. The first one is that hydrogen from renewable energy resources, most renewable energy resources, is quite expensive. And the reason for that is that hydrogen produced from renewables has electricity as an intermediary. And electricity is a fairly high value and also fairly high cost commodity. And then to produce hydrogen from that becomes quite expensive.

Let us take a look at some of the numbers. For example, if we take photovoltaics making electricity at 2 cents a kilowatt hour, which is quite optimistic, the hydrogen that comes from that is about $10 a million Btu. Compare that to hydrogen from natural gas, it is about $5 per million Btu. In other words, the photovoltaic-derived hydrogen at 2 cents a kilowatt hour is twice as expensive as that from natural gas.

When you take, for example, also hydrogen from coal, we should get that for about $6 to $7 a million Btu. So, again, comparing that with hydrogen from photovoltaics, we are about 30 to 40 percent cheaper getting it from coal.

The important points to make here are that, first of all, photovoltaic electricity at 2 cents a kilowatt is very optimistic. SERI projects it will take until 2030 just to get to 4 cents a kilowatt hour with an aggressive R&D program. That is going to up your cost of hydrogen to $20 a million Btu. SERI projects that PV cost of electricity will be about 10 cents a kilowatt hour in the year 2000, which ups again your hydrogen cost to $40 per million Btu.

Another point to make with regard to that is that if indeed we made a breakthrough in photovoltaics and did achieve electricity at 2 cents a kilowatt hour, what would happen is the vendor of that electricity would not be making hydrogen, which is just barely economic or not economic at all at $10 per million Btu, he would be selling electricity for 5 cents or maybe 10 cents a kilowatt hour.

Now there is a big exception to this, and I will get to that in a second. So, anyway, the first conclusion is that hydrogen, from most renewables, is quite expensive.

The second point I want to make is more along the lines of R&D. With regard to the research and development, if indeed society is dedicated to integrating renewables and hydrogen, the most important thing we can do is to lower the cost hydrogen and lower the cost of fuel cells. If we are not dedicated to that, but we are just dedicated to clean, efficient energy, one of the most important things that we can do, or two of the most important things are again lowering the cost of renewables and lowering the cost of fuel cells.

This bill does not seem to expand that, but diverts us away from that overall objective. And I think that that is a major missing link.

The third conclusion that I want to come up with here deals with the benefits of hydrogen. And let me get my notes out here. It deals with the use of hydrogen in vehicles and using hydrogen that comes from biomass resources. It has been stated here by the three previous speakers that the vehicle application of hydrogen makes a great deal of sense. And it makes sense for two reasons. One is that the most costly fuels are used for vehicle applications, so therefore, hydrogen can compete better. And the second point that the folks made before me as well is that hydrogen is used very efficiently, between 2 and 3 times more efficiently than conventional fuels in vehicles.

These are two very good reasons to use hydrogen in vehicles, provided we can develop a fuel cell that will be cheap enough to operate these vehicles. The second point I want to make is hydrogen from biomass. I talked about hydrogen coming from other renewable resources, speaking here of solar, electric, and wind as being quite expensive. That is not true in the case of hydrogen coming from biomass.

Well, what is biomass? Biomass are plants that are obtained or grown for energy purposes. Why biomass? Well, there are two primary reasons. One is that biomass will produce electricity cheaper than other renewable energy resources. Instead of producing it at $10, $20, or $40 per million Btu, we can obtain hydrogen from biomass, just gasifying it like you do coal, for about $6 to $7 a million Btu. So it is cheaper.

And the second benefit of biomass is that folks that have done assessments of the penetration of different renewable technologies in the future have concluded that biomass is by far and away the most significant of the renewable resources, which is a surprise to a lot of people. There are three independent studies that I am aware of. One of them is the potential of renewable energy technologies done by the National Labs; it is a National Lab white paper. And it concludes that in the year 2030 that two-thirds of our renewable energy will come from biomass.

The National Energy Strategy, the data that went into that suggests that two-thirds of our renewable energy will come from biomass. The founding president of EPRI did a study that looked out to the year 2060 of what energy requirements would be and what would provide those energy requirements. Again, the predominant form of renewable energy in that year he projected would be biomass.

So another way of putting it, looking at these folks' data, is that biomass will produce a third more energy than all the other renewables combined. So it is a very important renewable resource.

So, now, getting to the bill, after reviewing these three conclusions, I think it is very important that we take a look at biomass early on because of two reasons. One is there is no great magic to taking solar electricity, making electricity and electrolyzing water. I would say we are not going to learn anything technically by doing those sorts of demonstrations, and we are only going to learn that that is a very expensive way to go.

On the other hand, going forward with biomass is something that is not being done in any concerted, dedicated sort of way, and there is a real opportunity there. I think another thing that the bill could take a look at is how we are going to evolve from today's fossil-derived hydrogen to biomass-derived hydrogen and ultimately to other renewable-derived hydrogen. As I pointed out, the cheapest hydrogen comes from methane, and then from coal, and then from biomass. How are we going to progress there and what is the timing associated with that and how that compare with electricity? I think that is a very important need.

The last point is sort of a separate comment on the bill, and it proposes a demonstration of hydrogen for energy storage application for electric utilities. We at EPRI have been looking and evaluating that since I have been there for 18 years, and it just does not work out. If somebody would return the Senator Proxmire Golden Fleece awards, I think this would get it if we would fund something like that. The efficiency just is not there.

You lose about 50 percent of the energy in converting electricity to hydrogen and then back to electricity again. So I would certainly not encourage that we move forward with something that is only going to prove to be too expensive.

That is a summary of my comments.

[The prepared statement of Dr. Birk follows:]

PREPARED STATEMENT OF DR. JAMES R. BIRK, DIRECTOR, STORAGE AND RENEWABLES DEPARTMENT, ELECTRIC POWER RESEARCH INSTITUTE, PALO ALTO, CA

Mr. Chairman, Members of the Committee: I am James R. Birk, Director, Storage and Renewables Department, at the Electric Power Research Institute (EPRI).

EPRI was established by the electric utility industry in 1972 to conduct a broad research and development program for the entire electric utility industry and its customers. EPRI's R&D mission is to discover, develop, and deliver advances in science and technology for the benefit of member utilities, their customers, and society. EPRI is supported by voluntary contributions from investor-owned, government-owned and cooperatively-owned electric utilities across the nation.

EPRI has been actively involved with hydrogen R&D since 1974. We've been an active participant in world hydrogen conferences, we've maintained close contacts with both domestic and foreign organizations involved with evaluation and/or promoting hydrogen's future, and we've provided technical support and analysis of hydrogen systems to the utility industry. While EPRI does not have a significant level of support for hydrogen energy-systems per se, we have major programs in related areas such as fuel cells, coal gasification and biomass production and conversion. When viewed in their totality our programs are significant steps toward a hydrogen energy infrastructure in the next century. We are also developing wind turbine and photovoltaic (PV) technologies that are suggested by many as an important partner to hydrogen energy systems.

I've previously testified before a Congressional subcommittee on the benefits of hydrogen as an energy carrier (Hearing on H.R. 2541, A Bill to Establish A Hydrogen Research and Development Program, before the Subcommittee on Energy R&D, Committee on Science, Space, and Technology, U.S. House of Representatives, September 23, 1987). Like many supporters of hydrogen, I stated in that testimony, and several times since, the numerous and well-known attributes of hydrogen: (1) producible directly and/or indirectly from any fuel, (2) storable and shippable, (3) efficiently and cleanly usable, and (4) many subsystems are technologically ready now.

While many opportunities will arise for hydrogen energy systems, hydrogen is neither a needed nor desirable partner for many of the renewable energy systems in the foreseeable future. For example, as I will discuss, the simplicity and elegance of combining hydrogen with wind or PV energy systems does not stand up to objective scrutiny. Furthermore, the keys to success of integrating hydrogen and renewables are, by far and away, to lower the costs of renewable energy systems to inexpensively make hydrogen and lower the costs of fuel cells to cost effectively make electricity from hydrogen. In other words, regardless of one's attitude toward the integration of hydrogen and many of the renewables, the resulting research and development program to expedite hydrogen and renewable energy systems, whether separately or combined, would be nearly the same!

EPRI and a growing number of electric utilities are strong advocates of renewables. We see a time in the not too distant future when electric utilities will have a portfolio of renewable technologies that are cost-effective in their own right and are inherently environmentally acceptable. We at EPRI are dedicated to achieving that objective. We have been working with our utility advisors on a substantially expanded plan for renewables and storage. We are proud of our ongoing programs to develop wind and PV technology with the objective of delivering wind-derived electricity at 5¢/kWh by 1994 and 3.5¢/kWh by 2005 and PV electricity at 8¢/kWh by 2005. Our challenge to the proposed early marriage of many of the renewables and hydrogen is not a challenge to either renewables or hydrogen, separately.

Now let's look at the issues of integrating renewables and hydrogen. Photovoltaics directly produces electricity and not hydrogen. Wind generates electricity with a mechanical generator. It, too, does not directly generate hydrogen. In order to expend the cost and energy to convert the electricity from wind and photovoltaics into hydrogen, compelling justification is required. This is particularly true if we have, at a later point, to expend additional cost and energy to reconvert the hydrogen back to electricity. The efficiency of converting electricity to hydrogen and back to electricity again is 50% at best; i.e., half the initial energy is lost. Only in very special circumstances does such compelling justification exist. Such circumstances typically involve either very long distance transmission needs (thousands of miles), very long storage needs (days), or applications (e.g., transportation) where storage portability is essential. Thus, for most applications, solar and wind resources can provide electricity at higher overall efficiency and lower cost without hydrogen as an intermediary. Also, the low efficiency for interchanging electricity and hydrogen, along with high capital costs, precludes hydrogen from being a cost-effective storage medium for electric utility application.

Let's briefly look at the economics. Assuming that wind or PV provides electricity at a very attractive 2¢/kWh in the future, the cost of hydrogen from these sources has been suggested to be as low as $9/MBtu, with the most optimistic assumptions, and $13/MBtu with more realistic assumptions. Since natural gas now costs about $1.50/MBtu, hydrogen would be uncompetitive even considering its use is cleaner

and more efficient than natural gas. Even if $9/MBtu hydrogen would become competitive, organizations producing wind and PV electricity wouldn't be selling it for 2¢/kWh to make $9/MBtu hydrogen, they'd be selling it at market value. Furthermore, we note that hydrogen produced from natural gas today costs about $5/MBtu and the future cost of hydrogen from coal (at $1.5O/MBtu) is projected to be $6-7/MBtu. This discussion of hydrogen costs from different fuels tells us very dearly that we don't have to wait until solar electricity is 2¢/kWh. That could be a long wait since the National Laboratories Report on "The Potential of Renewable Energy" suggests PV costs won't be any lower than 4¢/kWh by 2030 even with a very aggressive RD&D program. We can obtain less expensive hydrogen from other sources and exploit hydrogen as an energy carrier much sooner than that.

Proponents of solar/hydrogen integration are actually doing a disservice to hydrogen as an energy carrier by implying that we have to wait until PV or other solar electricity costs drop to 2¢/kWh in order to consider hydrogen energy systems. We need to do all we can to get PV to 2¢/kWh and all we can to pursue opportunities (e.g., fuel cell development) for inexpensively using hydrogen. But we don't need to integrate the two now. Such an integration is superficially appealing, but of little practical benefit. The Project Management for the German renewable/hydrogen program supports "separate development paths of solar and hydrogen technology in the coming decades" (N. Stump and P. Malinowski, Hydrogen Economy as an Answer to Greenhouse Effect?, Conference on 21st Century Electrical Generation, San Francisco, December, 1989). The paper also suggests that the "possibilities of non-fossil hydrogen as a potential energy carrier for the near future should not be overestimated."

Hydrogen is more likely to be an economically viable alternative when it is produced in competition to (i.e., instead of) electricity, not produced with electricity. Hydrogen can be produced directly and thus most economically from natural gas, coal, or biomass (plants grown or obtained for energy). Alternatively these fuels can be used through combustion or gasification/combustion to produce electricity. The choice between electricity or hydrogen as the energy carrier is dependent upon a number of factors: environmental impact of production; transmission costs; economics of energy management and storage; and environmental impact, ease, and efficiency of use.

If solar and hydrogen energy are to be effectively integrated, hydrogen must be generated directly from the sun's energy and not produced from electricity, which is a highly valuable form of energy. Several ideas are being pursued to eliminate the conventional electrolysis step in converting sunlight to hydrogen and to achieve direct generation of hydrogen. These ideas are either photoelectrochemical or genetically engineered biological processes. If hydrogen and solar are ever to be integrated, these processes are conceptually the most attractive, but require long-term and high risk R&D. We encourage continued and even expanded research on these ideas and processes.

One potentially promising renewables/hydrogen alternative is the concept of biomass to hydrogen for transportation applications. Hydrogen has some unique features for transportation: cleanly used, efficient conversion with fuel cells and electric motors to power, and high energy per unit weight for air transport. However, hydrogen for transportation is also threatened by some formidable challenges; namely, handling, safety, and storage. In comparison to gasoline, gaseous hydrogen requires twenty times the volume and liquid hydrogen requires four times the volume for an equivalent amount of stored energy. Metal hydrides and activated carbon offer promise for substantially reducing the volume requirements of hydrogen, but further R&D is needed to realize and demonstrate this promise. If hydrogen can be developed into a viable transportation fuel, the most economical sources for the foreseeable future would be natural gas, coal, and biomass.

There are numerous niche markets for hydrogen, starting of course with existing applications in space power, hydrogenation of vegetable oils, chemical production, and hydrocracking of crude oil. Other markets may also evolve. For example, a large wind farm could provide hydrogen to supplement natural gas in an existing pipeline assuming wind derived electricity drops to 3.5¢/kWh, new electric transmission facilities would be required, and natural gas prices escalate substantially. Niche markets are an important, if not essential, ingredient to expedite the use of hydrogen as an energy carrier.

In conclusion, I will reiterate the key points I've made in this message:

- Since solar and wind energy inherently generates electricity, these resources can provide electricity at higher efficiency and lower cost without hydrogen as an intermediary.

- Natural gas, coal, and biomass can be directly reformed/gasified into hydrogen. As a result, they are the most economic fuels for hydrogen production in the foreseeable future.
- Electricity and hydrogen are interchangeable commodities but more than one interchange is generally unaffordable for the foreseeable future. As a result, hydrogen for electric utility energy storage is unlikely to be cost effective.
- We should not divert our R&D resources for hydrogen and for renewables, except for biomass, to enhance their integration. It will happen when the economics are right.
- The most important needs in hydrogen are (1) achieving highly-efficient, direct conversion of solar energy to hydrogen through photoelectrochemical or biological processes, (2) developing low-cost storage and fuel cell conversion technologies for transportation applications, and (3) identifying and responding to early cost effective niche markets.
- The most energy significant and potentially viable opportunity for hydrogen may be as a transportation fuel derived in the long term from biomass gasification.

Based on the text and conclusions above, we provide the following specific suggestions on S. 1269 for your consideration:

- Section 4(2). Add "biomass" as a renewable energy source.
- Section 5(a)(1) and Section 6. Biomass should be considered a leading candidate for a development, construction, testing and demonstration program (Hydrogen from other sources is too expensive and there are no major technical advances that need to be demonstrated).
- Section 5(b)(2). The "Plan" should include something along these lines: Based upon an evaluation of the costs of hydrogen over time from both fossil and renewable resources, a cost-effective transition from methane to coal to biomass and, ultimately, to other renewables is to be suggested for the production of hydrogen and compared to the production of electricity for a variety of energy-significant applications.
- Section 6. Utility Load Leveling System. The low efficiency, high cost, and lack of any major technical obstacles that aren't already being addressed, doesn't justify demonstration of a hydrogen load leveling system.

Senator FORD. Thank you very much, Dr. Birk. You did very well.

Dr. Ogden, you mention in your comments that a number of transportation projects are under way. Would you elaborate on those for me, please?

Dr. OGDEN. Yes, I can mention a few that I am aware of.

Senator FORD. And you might just say where they are if you have that idea, and how far along they might be.

Dr. OGDEN. Well, the ones that I am aware of, Daimler-Benz and BMW in Germany have had hydrogen vehicle research and testing programs for years, really, since the mid-1970's, and they are continuing with those programs. Also, as Dr. Prater mentioned, there is a demonstration project being planned in British Columbia. Hydrogen fuel cell vehicles are being developed by Ballard, by Energy Partners in Florida. There is a group in Belgium called ELENCO that has been looking into this.

The Pennsylvania State Energy Office, in conjunction with Roger Billins, are building a fuel cell vehicle. And the South Coast Air Quality Management District is building a small photovoltaic electrolysis experiment, and they are going to power hydrogen vehicles with this. Initially, they are going to use internal combustion-engine vehicles, but in the longer term they would like to use fuel cell vehicles.

Those are the ones that I am aware of, and there may be others.

Senator FORD. Doctor, under BMW's prototype, liquid hydrogen must be stored at minus 423. This BMW prototype which uses liquid hydrogen loses up to 2 percent of its fuel every day, com-

pared to 1 percent per month for gasoline. And for liquid hydrogen, the current cost of the tank is estimated at $26,000. The BMW car has a range of 190 miles per tank, however, the refueling process takes up to 1 hour because of the care required when handling the liquid hydrogen. And I think Mercedes has about the same kind of problem.

Are we looking at something that is going to be realistic?

Dr. OGDEN. Well, these problems just point out the crucial importance of developing fuel cell vehicles. I might mention that both the Mercedes and the BMW project use internal combustion engines, which are similar to what we use in our gasoline cars, for powering their vehicles. One of the reasons they use liquid hydrogen is that that is more compact to store on board. All of the various storage systems for hydrogen are bulkier and heavier than gasoline.

With an internal combustion engine it is so inefficient really that you have to use something possibly like liquid hydrogen, which has a lot of problems. With a fuel cell vehicle, the vehicle itself would be efficient enough that you could have gaseous hydrogen storage, even though it is bulkier, you would be able to store enough energy on board to go a reasonable range.

With gaseous storage you would avoid all of these problems. You could have fast refueling, on the order of 5 to 7 minutes if you had a compressed gas storage tank in your car, instead of an hour for liquid hydrogen. You would not have these problems of a very cold liquid boiling off. In other words, with a fuel cell car, you could have a gaseous storage system and refueling system that would avoid all of these problems, and the system would like very much like what our gasoline cars look like today, really, in terms of there being some place you would go to refuel at a filling station and be refueled quickly.

Senator FORD. Whereas the fuel cells are important on the basis I guess that you maybe could have a smaller tank and carry less and have less of a problem. I know most people, in doing some studying for this hearing today, have a perception that hydrogen is more dangerous than natural gas or gasoline. This is not borne out by the years of experience, I understand. Is that correct?

Dr. OGDEN. That is correct. Yes.

Senator FORD. Dr. Prater, you have a lot of believers in your fuel cell out there because you get a lot of venture capital. Is that correct?

Dr. PRATER. That is correct, sir.

Senator FORD. You do not have to answer this question, but from what arenas do you get your venture capital? Does it just come from individuals? Does it come from industry? Does it come from basic companies?

Dr. PRATER. I am very happy to answer the question, actually.

Senator FORD. Lots of time you are prying, and we cannot even get Common Cause to release the names of those who fund them, you know.

Dr. PRATER. We took a substantial venture capital investment, about 7.5 million Canadian dollars 2 years ago, and 2 days ago another 4 million from the same group of investors. When we took venture capital it was important to us not only to have the money

to operate on, but also to have a group of investors who would provide us with a sense of staying power. Because we are a small company, and one of the problems we face is the question of, are you going to be around next week.

Our investors, sir, are British Gas, the British gas utility company; a Swiss electric utility called Motor Columbus. In the United States there are three venture capital organizations invested in us, one of which is located here in the Washington area has as its investors the major U.S. gas and electric utilities. A second located in Boston has as its major investors large corporations. So indirectly Monsanto, Nippon Steel, Broken Hill Proprietary from Australia are invested in us. And finally, in the United States, Xerox Corporation has invested in us.

In Canada there is a small venture capital company in Vancouver; the Government of Canada through its venture capital arm; and Metropolitan Life Insurance Company.

Senator FORD. Well, I hope Metropolitan does well, because I am looking forward to them paying me some day.

[Laughter.]

Senator FORD. I hope that you do well for them.

Dr. PRATER. Thank you.

Senator FORD. Mr. Serfass, you said that vehicles are the best near-term use of hydrogen and that we need more Federal support, if I made my notes right. What kind of dollars are you thinking about as it relates to Federal support in the research and development in this arena?

Mr. SERFASS. I would be hard pressed, I suppose, to answer directly with a dollar figure, Mr. Chairman. Let me talk around that a bit.

Senator FORD. You sound like a bureaucrat.

[Laughter.]

Mr. SERFASS. The keys are the fuel cell technology and the storage system. The bill identifies several storage systems. I might add that liquid hydrogen is one of the storage systems that is relevant to hydrogen storage that is not directly identified in the bill and probably should be. But it identifies hydrides and activated carbon and compressed gas. And all of those need to be investigated and supported until we can determine what the proper storage technology is for a vehicle.

You need to store what is otherwise not a terribly energy dense material in a relatively small amount of space. As Dr. Ogden said, one of the benefits of fuel cells, in addition to the tremendous environmental characteristics of the technology, is that it uses the fuel 2 to 3 times as efficiently. And so you need the fuel cell as the propulsion system with electric motors, and that, in combination with the storage system, needs to have a capital cost of, let us say, several hundred dollars a kilowatt. We are no where near there today I do not believe, but that is where the focus, as Dr. Birk said, of the research funding has to go for at least the vehicle application.

The funding for developing the renewable resources that can produce the hydrogen that together give you an environmentally benign system, of course, is also crucial. So, it depends on how broad you want to define the hydrogen program. But I would suggest that a program focused on fuel cells and energy storage sys-

tems ought to be at least in the tens of millions of dollars, and not in the $3 million range.

Senator FORD. Does any member of the panel understand what General Motors is doing with their electric car? They are just gung-ho. I did not have an opportunity to hear the statement at a recent conference. Does anyone know, Dr. Birk or anyone, what General Motors is doing or how far they are along with their electric car? And this ties in with what we are trying to do here. And they are saying that they look forward to a breakthrough fairly soon. Does anybody have any idea about that? It must be a secret.

Do you have a contract with them, Dr. Prater?

Dr. PRATER. Yes, we are working with General Motors as a subcontractor on the DOE program to demonstrate a fuel cell powered vehicle. We have been in discussions with the various people within General Motors who are involved in their electric vehicle program. And it is my perception, although I certainly would not want to speak for General Motors, that within the last year or so, prompted principally by the decisions that have been made within California, that General Motors is serious about producing electric vehicles, and that they see batteries as one such vehicle, but I think they also very definitely see fuel cell powered vehicles as the longer-term, ultimate solution.

Senator FORD. Yes, they seem to be pretty gung-ho.

Dr. Birk, coming from a coal state, I am quite interested in using coal for hydrogen or anything else. I noticed a cigarette that was being manufactured and sold in Great Britain that has a coal filter. And we are trying to put it on highways and everywhere else that we can at the moment. But biomass is something that intrigues me. Is it true that we might have small, individual, residential biomass energy development units in the foreseeable future?

Dr. BIRK. Well, I doubt that they would be that small. Biomass, by its inherent character, is going to be relatively small. We will not have 1,000 megawatt biomass plants. They will probably be more like 100 megawatts because of the nature of resource; you have to go out and harvest it and bring it in. And the most expensive portion of that is the harvesting and transportation of the biomass back to the power plant or whatever plant it might be.

So it is going to be a regional type of a resource. And I think that is an advantageous benefit, particularly for farm states like my home state of Iowa, and others. Wisconsin and Minnesota might benefit for two reasons. One is there is a lot of land, as you know, set aside, that folks are not growing things because farmers have become too productive. So this is an opportunity to use that land in a very productive way.

Senator FORD. What would they be using? What would they be producing?

Dr. BIRK. Well, there are a lot of options. I would say the favored one seems to be wood, just fast-growing wood. Oak Ridge National Laboratory has been looking at a number of different wood species. I think poplar trees are one of the more common ones. And the objective in that biomass program is to get the growth rate of the wood up to economically viable levels.

If you go to a forest, they may grow at about a ton per acre per year, and what we are after in a biomass plantation would be

about 10 times that. And that has actually been seen on cloned trees.

Senator FORD. Cloned trees?

Dr. BIRK. Yes.

Senator FORD. They are doing better with trees than they are with people.

Dr. BIRK. Right.

This identical type of tree reproduced that happened to be very fast growing.

Senator FORD. The storage problems bother me, and we are all talking about storage problems. The BMW and the Mercedes have shown that they lose so much more, 2 percent per day, versus gasoline which is 1 percent per month. How soon do you think the storage problem will be overcome? Does anybody have any guesstimate on that?

Dr. PRATER. Well, I would certainly comment that we would love to see a dramatic improvement in storage and yet, at the same time, I think existing high pressure gas storage can be satisfactory in the near term, in terms of providing the range necessary, certainly for buses and the like, and I think for personal vehicles. Now, that does not mean it cannot be improved; it is just on the edge today.

Senator FORD. Why did we go to buses instead of vehicles?

Dr. PRATER. The bus is an ideal first for both demonstration and commercial vehicle for two reasons. One, it is less volume constrained. That is, you have got a little bit more room to play around with. And secondly, the percentage of the total life cycle cost of a bus, represented by the engine and storage system, is a comparatively small fraction. So that even at today's or near term projected costs for fuel cells, one can imagine that a fuel cell powered bus might perhaps have a life cycle cost only 3, 4, or 5 percent greater than present buses.

What that means is, a 3, 4, or 5 percent increase in fare for a nonpolluting bus. Whereas bus companies buy on the term of a life cycle cost, you and I do not buy our automobiles that way. And so a bus is a better place to start.

Senator FORD. I noticed in the design of the bus, since I mentioned earlier that the perception is that hydrogen was more dangerous, that your storage tanks are underneath the seats where the passengers will sit. And I am not sure how many people want to go and sit on top of those tanks. There is going to have to be a public information program to get people to ride the bus.

Dr. PRATER. You are absolutely right. There is no question about that.

Senator FORD. Well, give me one. Today, I am right on one.

[Laughter.]

Senator FORD. Being in politics, getting one right a day is very fortunate I think.

Dr. PRATER. And again, this is one of the reasons that we see demonstration programs today being important. It is important to demonstrate that safe buses can be designed. I would point out, however, Mr. Chairman, that certainly in British Columbia we have wide experience with natural gas fueled vehicles. Essentially, all the taxicabs in Vancouver are powered by natural gas. So there

is a substantial body of experience with gaseous fuels. And in Vancouver it is very well accepted.

Senator FORD. Well, years ago on the farm I used a tractor that was powered with natural gas. I had no problem with it at all. The maintenance was a great deal less, and the life time of the farm tractor was much greater. So I can attest from personal experience the use of natural gas. We get back to Dr. Birk's statement, we know it is cheaper with natural gas, and we also know it is cheaper with coal, and yet we are trying to get into renewables.

Maybe with the experiment, if we move on, we might be able to find some answers that we are trying to stumble into now. I am not sure stumble is the right word, but you never know, tomorrow you may find the answer that would give you the kind of dollar figure, but here is one that you go on and drive with and would be environmentally acceptable. We have to make judgments from statements from people like you. And I am certainly glad that everybody does not agree on everything, because if you did, we would be very concerned on this side that we would not have anything to do.

[Laughter.]

Senator FORD. A fellow went through my county one time. He said, do the people agree on things here. And another fellow said, no, if you are arrested, plead not guilty, because we cannot find 12 people to agree on anything.

[Laughter.]

Senator FORD. So that is kind of the way it is. There will be some questions from other Members of the committee who are not here. As you probably know, we are active on the floor today. We also will have questions in writing to all four of you, and we ask that you respond in a timely manner.

One thing I would ask you to think about a little bit, and if you want to that is fine, and if you do not it is all right also, but it appears that we are going to have some problems with the Department of Energy as it relates to moving in this arena, and that they are not supporting this piece of legislation. If you have some thoughts of what we might be able to do to arrive at a Henry Clay position on this, that we might move it on into another arena.

You are talking about tens of millions and we are talking about $2.6 million or $2.8 million, or something like that. But I do draw your attention to the military interest in hydrogen, which is about $30 million or so, and there may be something we could tap into there that would give us some push in this area. I think our problem here is to try to reduce the cost. And if we continue to nickel and dime some of these projects together, it is just going to keep people alive financially to move on to the next step, and not move us in a very fast direction.

We want some venture capital, do we not, Dr. Prater?

Does anyone have any comments you would like to make before I end this hearing?

[No response.]

Senator FORD. If not, you all are mighty nice to come today, and I appreciate your patience and your cooperation and look forward to working with you in the future.

[Whereupon, at 10:46 a.m., the hearing was adjourned.]

[The subcommittee received the following statement for the record:]

PREPARED STATEMENT OF JOHN H. PERRY, JR., CHAIRMAN, AND JERRY J. JONES, PRESIDENT, ENERGY PARTNERS, WEST PALM BEACH, FL

Mr. Chairman and Members of the Subcommittee, my name Is John H. Perry, Jr., and I am the founder and Chairman of Energy Partners. With me to today is Mr. Jerry Jones, who is the President of Energy Partners. We are pleased to be here to share with you our thoughts on the Bill proposed by Senator Harkin, the renewable energy portions of the FY 1992 Budget, and to offer our appraisal of business opportunities existing within the technologies that make up the renewable energy sector, especially hydrogen. We will also try to provide some tangible examples of how we believe government and industry can work together to accelerate the evolution to an energy future that offers greatly reduced environmental pollutants.

I have personally provided funding and been involved for over 25 years in developing and testing energy components and systems based on clean, renewable, energy sources. This has encompassed technologies as diverse as windmills, photovoltaics, fuel cells and hydrogen-powered internal combustion engines. In the late 1960's my companies built and powered the original underwater Hydrolab (for Astronaut training) with hydrogen-fed fuel cells. In the 1970's and 1980's we built manned submersibles powered by several types of fuel cell systems, including what we believe was the first use of the Proton Exchange Membrane or PEM cells in 1989. We built electrolytic conversion systems that converted seawater into hydrogen-rich methanol. We call this our SEAFUEL process, which is patented. All of these technologies were developed within the Perry Companies that were the forerunners of Energy Partners. In every case, our first demonstrations of these technologies have led to broader commercial involvement and, in some cases, commercial products.

Energy Partners is a company committed to the practical demonstration and application of renewable energy systems technology. We have elected to take this course of action because we felt someone in the private sector needed to be encouraging the development and providing a market for the many sub-technologies that make up a complete renewable energy system. As the name "Partners" implies, the Company has entered into strategic written relationships with manufacturers, universities and organizations that have technologies that are applicable to such systems. Our primary focus is on hydrogen using systems.

We feel this approach will also allow a close cooperation between industry and government through mutually agreeable joint industry and government demonstration platforms, which will increase the public awareness of what can be done with the existing state of renewable energy systems. This is particularly directed toward the area of fuel cell power systems applied to the transportation sector. The seriousness of our conviction is evidenced by our proposed cost share program in FY 92, whereby we are proposing to provide $1.5 million of our funds, in combination with a requested $1.8 million in government funds, to build the fuel cell/battery powered, zero emission vehicle, *Green Car*, that provides an important stepping stone in the long term solution for our nation's transportation system.

For this first cooperative effort, Energy Partners has teamed with Consulier, a U.S. Department of Transportation approved Original Equipment Manufacturer (OEM) of automobile bodies and other equipment. The Consulier car has a unique space-age advanced composite primary structure, which is very light in weight, while maintaining the necessary strength for durability and safety. Consulier has the excellent combination of automotive expertise while being small enough to change directions and take the risks which innovators must take. For technical assistance in addition to its own in-house capability, Energy Partners intends to work closely with both Georgetown University and Argonne Laboratories. While the first phase of the project is to deliver a zero emissions proof-of-concept car in about 13 months, the entire *Green Car* program is structured in six phases that will result in the production of such automobiles in meaningful quantities.

Mr. Chairman, we are encouraged by the budget request for the Conservation and Renewables program that has been submitted for FY 92. It is certainly a step in the right direction compared to what we have seen over the past ten years; however, it is lacking in the area of hydrogen utilization. We see solar energy up to $142.9 million (as compared to $129.4 million in FY 91), yet only $2.6 million is targeted in FY 92 for Hydrogen Research, Development and Demonstration (RD&D). This would appear to us who are active in developing this technology as very short-sighted. Similarly, in the Transportation Budget, there is only $9.5 million for fuel cell vehi-

cles, and at present these funds are allocated to a fuel cell bus program and a General Motors Contract. There is little, if any, money for the small, innovative, risk-taking kinds of projects that the smaller companies of our country have routinely done. These are the kinds of projects that lead to the formation of economic forces in the marketplace, like the Polaroids and Xerox's of today's economy.

In the area of Fuel Cell vehicles, we personally know of at least four viable University and Industrial entities which can do an excellent job of integrating state-of-the-art fuel cell systems into transportation vehicles. The zero pollution and high efficiencies of these systems should give them substantially higher priorities than we see in this budget. This would lead us to believe that a Fuel Cell Vehicle budget closer to $20 million is warranted. This would then allow DOE to be responsive to Title VIII, Sec. 807 of the Clean Air Act Revisions. We would like to point out the Hydrogen Development Act under discussion today would go a long way towards improving the DOE Budget picture in this area. We would therefore recommend that this act be included in this Committee's Authorization Bill.

In the area of hydrogen research, per se, we feel that the $2.6 million requested is not responsive to either PL 101-566, the Spark Matsunaga Hydrogen Research and Development Act, or to the level of importance that Hydrogen RD&D should have in the U.S. This is graphically evidenced by the recent Canadian initiatives, whereby the British Colombia provincial government, alone, announced its intention to fund $100 million (Canadian) for Hydrogen RD&D. The province of British Columbia has a population of about 3 million, or roughly half that of New York City. The United States needs a level of effort that is at least significant enough to allow us participation with Canada in an effort that could be so vital to all of us in the future. We in the U.S. will not reap benefits without meaningful participation. We must take a leadership position.

One area that also seems to us to be lacking in the implementation of renewables is tax incentives. We are aware, of course, of the general R&D Tax Credit and of the Solar and Renewable credits which have such a fight getting renewed from year-to-year. However, Mr. Chairman, history has shown us that a sound, dedicated approach using tax incentives enabled the development of the strong, powerful gas and oil industry that we have in the United States today. We believe that the Energy Tax Act of 1978 needs to be revisited, especially in the areas of Business Energy Tax Credits. Tax credits for business investments in technologies which use or produce alternative forms of energy will create the incentive for numerous partnerships, such as ours, to substantially participate in the furtherance of our national goals in renewable energy through meaningful inputs of private sector funds. We would like to see initial credits in the 50-70% range to create the needed "jump start" of such partnerships. Considering the $500 million per day cost of Desert Storm, this is a small and sound investment.

Virtually all opportunities in the private sector regarding development and application of renewable, non-environmentally-damaging energy systems require a long term investment strategy and mentality. This is because the financial returns on such investments will probably not begin to yield favorable results for upwards of 10 years. There are an increasing number of us in the business community, however, that believe that this investment in dollars and technology must be made now for the security and well-being of the future generations of both the United States and the planet Earth. This is in spite of the lack of short-term financial objectives. It is honorable work that needs undertaking.

Most, if not all of us here, know that we as a nation use almost a third of the fossil-based fuels harvested worldwide. We also know that we are paying a price far beyond that reflected in our utility bills or posted at the local gas station for the use of these fuels, both in our industrial and private lives. The final price is reflected across a broad spectrum of our economy and partially includes items such as health costs, political aid packages, military expenditures, environmental clean-up costs, and the results of increased global warming. Of course, as we try to mitigate the results of our addictive use of fossil fuels, we also spend an additional billion dollars annually in research to try to find ways to reduce the negative effects derived from their use.

Given this scenario, it is not merely desirable that industry and government find meaningful and fruitful ways to cooperate in the development and application of renewable, environmentally-friendly energy systems; it is mandatory. Private industry must be "incentivized" to look beyond short term profitability in the U.S. or we will find ourselves once again behind in an industry dominated by the Japanese and the Europeans. Japan in particular has historically supported, and is presently supporting the increased development, and even more importantly, application, of renewable energy technologies within their country.

Before we can look at recommendations as to how the government can support U.S. industry in a meaningful and constructive manner that will be of benefit to all U.S. citizens, we must first address the need for a unified, directed strategy. We believe the correct strategy is to support steady, meaningful, and measurable progress through active and joint support of demonstrations of the best renewable energy systems. This strategy will uncover subsystem weaknesses, and will force technological breakthroughs in areas that have the potential for such breakthroughs. I submit that fuel-cell power systems for use in the transportation sector of our economy is, and should be, at the heart of this strategy. The Harkin Bill provides the needed incentive to get activities like this underway.

The buzz words commonly heard in renewable energy today relate to our need to make the transition from fossil fuels to a "Hydrogen Age" or "Hydrogen-based Economy." We need to progress toward such a future, but we are not going to get to a fully integrated hydrogen economy in any reasonably predictable timetable. The data needed to give us a window into how and when that future will occur is unknown. We are going to get there, but the many hydrogen support infrastructures needed that are not existing today, will have to be developed and built, with at least the level of safety we have with fossil fuels today. The only things we can reasonably predict from our economic and engineering models done today are two basic "givens" for the deep future . . . hydrogen and electricity will be the energy currencies of the future, and the fuel cell will be the "silicon chip" of that future. Hydrogen and electricity will be "currencies" because they are complimentary. Each can be used to make the other, but better storage alternatives exist with hydrogen.

The fuel cell will be the "silicon chip" because there is not a single, present energy system application, either utility or transportation, that could not be performed by a fuel cell fueled by either hydrogen or a hydrogen-rich fuel. While the basic fuel cell uses hydrogen and oxygen as energy feedstocks to make usable direct current electricity, its byproduct is water; not carbon monoxide, carbon dioxide or nitrous oxide, but drinkable water. This water can be used again to produce hydrogen through electrolytic conversion. We firmly believe that the future holds great economic rewards to the country that leads in the development and application of fuel cells and their related technologies.

While we presently use hydrogen to power our spacecraft rockets, and as a feedstock for fuel cells onboard those spacecraft to power many systems (including life-support systems), the technology to build such systems is not presently economic. It has only been in the last several years that a newer class of proton exchange membrane (PEM) fuel cells have been developed. This is important because the cells have the potential to gain widespread use (particularly in transportation applications) due to their size, efficiency and power-handling abilities. They also have the potential to be cost competitive with fossil-fuel burning engines if they were manufactured in meaningful quantities to a receptive marketplace. We personally have applied such fuel cells in manned underwater submarines. They are presently being applied in a limited number of other programs by ourselves and others, mostly through government cost sharing programs. These systems sometimes solve previously unsolvable range, space, or heat problems, making them fall in the category of "enabling technology". There is another technology presently being researched in solid oxide fuel cells (SOFC). Sizes and power densities of the SOFC cells are even more promising than the PEM technology, and these cells are more forgiving of the quality of the feedstock fuel.

By developing and successfully demonstrating fuel cell technology in the transportation sector, the market needed to stimulate the fueling and support infrastructures will naturally follow. At the appropriate time, again within the overall strategy objectives, similar shared funding programs can be targeted at specific support technologies that are needed but have not kept pace with the transportation "vehicle" development.

The governmental and industry departments and organizations to make a joint industry-government program work are already in place. The Secretary of Energy and the Hydrogen Technical Advisory Panel (established under Section 108 of PL 101-566) already have the people with the dedication to make meaningful progress. Broad industry support for this approach has been indicated through the National Hydrogen Association. The only lacking ingredient is budget commitment on a meaningful scale, backed up by a Bill like Senator Harkin's.

I urge the Subcommittee to take a leadership role and support this industry/governmental initiative and other initiatives that support the strategic objectives outlined herein. Thank you for your attention.

APPENDIX

RESPONSES TO ADDITIONAL QUESTIONS

DEPARTMENT OF ENERGY,
CONGRESSIONAL AND INTERGOVERNMENTAL AFFAIRS,
Washington, DC, August 6, 1991.

Hon. WENDELL H. FORD,
Chairman, Subcommittee on Energy Research and Development, Committee on Energy and Natural Resources, U.S. Senate, Washington, DC.

DEAR MR. CHAIRMAN: On June 25, 1991, Dr. Robert L. San Martin, Deputy Assistant Secretary for Utility Technologies, Office of Conservation and Renewable Energy testified before your subcommittee, regarding DOE's hydrogen energy research program and advanced fuel cell programs, and S. 1269, the Renewable Hydrogen Energy Research and Development Act of 1991.

Following the hearing, you submitted five written questions to supplement the record. Enclosed are the answers to those questions.

If we can be of further assistance to you or your staff, please contact our Congressional Hearing Coordinator, Valerie Howard, on (202) 586-2032.

Sincerely,

JACQUELINE KNOX BROWN,
Assistant Secretary.

[Enclosures.]

Question 1. Does the Department have an opinion as to which renewable energy source offers the best chance to economically produce hydrogen?

Answer. Processes that first produce electricity and then produce hydrogen result in delivered hydrogen at a cost that reflects the cost of electricity. Today's electricity prices would result in hydrogen prices that are 2 to 3 times the target price of $10 per million Btu. Thus, renewable energy conversion systems that produce hydrogen without the intermediate electricity step are likely to be more competitive sources for hydrogen production than systems that rely on electricity, such as electrolysis of water. Examples of direct hydrogen production methods are photoconversion, such as photoelectrochemical or photochemical processes, or bioconversion from renewable biomass products. However, these approaches currently exhibit low conversion efficiencies and require additional research. Because of current generation costs, photovoltaic systems are not a likely near-term renewable energy source for hydrogen.

Question 2. When does the Department think it will be possible to produce hydrogen from renewable energy sources at competitive market rates?

Answer. Current transportation fuels, such as gasoline, diesel fuel, and natural gas, are relatively low cost. Electricity is several times more costly on an equivalent energy basis. Only certain renewable systems in favorable locations can provide competitively priced electricity today. It is likely to be a decade or more before renewable systems can produce hydrogen that can compete economically with the more traditional fuels.

Question 3. What is the Department's opinion of hydrogen powered vehicles, those powered by internal combustion engines as well as by fuel cells? Does the Department think that vehicles powered by hydrogen are technically feasible and would eventually be economical?

Answer. Hydrogen powered vehicles, using either internal combustion or fuel cell conversion systems, are technically feasible using current technology. However, due to the bulkiness of a readily adaptable hydrogen storage system and general non-availability of low cost hydrogen fuel, the range of an internal combustion vehicle

would be limited and its operating cost would be high. A fuel cell powered vehicle would be more efficient than its hydrogen heat engine counterpart but would still have range and operating cost shortcomings. In addition, fuel cell capital costs are still quite high and the purchase price of a fuel cell vehicle would be 3 to 5 times that of current vehicles. However, fuel cell research and development advances are expected to improve their relative economics.

Question 4. How much money is the Department currently spending on fuel cell research, specifically on fuel cells for use in automobiles that directly use hydrogen as a fuel?

Answer. All fuel cells can use hydrogen directly as a fuel. Of several fuel cell programs supported by the Department, at least 2 types, the polymer exchange membrane (PEM) and the phosphoric acid system, have potential application to vehicles. For PEM fuel cells, current annual spending is $6,914,000. In support of phosphoric acid fuel cells, the Office of Transportation Technologies' annual spending is currently $1,990,000, although $8.6 million has been spent on phosphoric acid fuel cells since FY 1987.

Question 5. What hydrogen production and storage technologies are the Department pursuing?

Answer. Research on hydrogen production includes investigation of photoelectrochemical and photobiological processes for direct production of hydrogen and development of multi-layer solar cells for indirect production of hydrogen. For hydrogen storage, efforts are underway in support of both metal hydride and super activated carbon technologies. Both of these approaches are solid forms of hydrogen storage and are potentially suitable for transportation applications. This research agenda is flexible and may be changed to respond to technology advancements.

BALLARD POWER SYSTEMS,
North Vancouver, B.C., July 10, 1991.

Hon. WENDELL H. FORD,
Chairman, Subcommittee on Energy Research and Development, U.S. Senate, Committee on Energy and Natural Resources, Washington, DC.

DEAR SENATOR FORD: Thank you for the opportunity to provide testimony before the Subcommittee on Energy Research and Development regarding S. 1269. My responses to your additional questions follow. I will repeat your questions for clarity.

Question 1. You testified that a study showed that a vehicle powered by a fuel cell using hydrogen would have the same performance and range as a gasoline powered automobile. Can such a car be built today? would such a car be cost competitive with gasoline powered cars? What disadvantages would be associated with such a car?

Answer. The study I referred to was a preliminary design and cost study conducted by Directed Technologies, Inc. (DTI) of Arlington, Virginia. If you would like to obtain a copy of that study, you may contact Ira Kuhn at (703) 243-3383.

DTI took the Ford Taurus as its study test bed. The first objective was to determine whether a fuel cell or fuel cell/battery hybrid power train could be assembled which would produce the same power and driving range as the internal combustion engine (ICE) powered Taurus, within the same total weight and volume constraints. The assumption was that, if this could be accomplished, the fuel cell vehicle driving performance would match that of the production Taurus.

DTI concluded that these design objectives could be met with hydrogen gas as the fuel stored in presently-available composite cylinders at 5000 psi and using motors and controls which are now available. The design assumed fuel cell performance which has been demonstrated in various laboratory forms but not yet converted into production prototype form. Specifically, DTI assumed fuel cell operation at 100 psi and the incorporation of light weight structural materials. Ballard has demonstrated operation at 100 psi, though its present production model operates at 35 psi. Ballard's present production model incorporates metal and solid graphite components, though laboratory models incorporating light weight composites are being developed.

Ballard and other potential fuel cell manufacturers could deliver the required fuel cell systems within 18 to 24 months, if required. The answer to your first question1 then, is that such a car could be built within two years with no requirement for technological breakthrough. Such a project would, however, require an engineering development effort.

DTI then considered the capital and operating costs of the fuel cell powered automobile and concluded that, in the near to medium term, the capital cost of the fuel cell power train would likely cost about twice that of the power train in the ICE

Taurus ($6,000 versus $3,000), but that the lifetime operating costs of the fuel cell—powered vehicle would probably offset that difference. Interestingly, DTI concludes that, because of the higher fuel efficiency of the fuel cell option, fuel costs (hydrogen for the fuel cell, gasoline for the ICE) would be less for the fuel cell vehicle.

DTI's capital cost conclusions are based upon fuel cell costs which require substantial reductions in amount of platinum and in the cost of the membrane electrolyte, as compared with present production units. These cost estimates are consistent with technology which has been demonstrated in the laboratory. It is reasonable to conclude that these estimates would be valid for relatively small production levels three to five years from now and that further reductions in cost would come with increased production levels.

Other than having a somewhat higher initial capital cost, the principal near term disadvantages of a hydrogen fueled, fuel cell powered car would be infrastructural. These would include limited availability of refueling sites and limited availability of service and maintenance manpower and facilities as compared to that available for the ICE car.

Question 2. Have the storage problems associated with hydrogen powered cars been overcome?

Answer. The DTI study concluded that equivalent range could be obtained with gaseous hydrogen stored in composite tanks at 5000 psi, but that the volume of such tanks would be about three times that of a gasoline tank for equivalent mileage. Interestingly, with an advanced carbon composite tank, the weight of the tank plus hydrogen was only marginally greater than that of the equivalent gasoline tank including fuel and weighed less than the corresponding tank plus fuel for a methanol fueled ICE car.

The major disadvantage to this storage approach is the high cost of such advanced cylinders. Even on the basis of projected materials cost alone, the carbon composite tank would cost over $2,000 whereas a glass fiber-wrapped cylinder would cost about $1,500.

In summary, then, hydrogen storage for a car is now feasible, but further improvements in on-board hydrogen storage are very desirable, both in terms of reducing volume and cost.

Question 3. How does the performance of a fuel cell powered car compare to that of a gasoline powered car?

Answer. The DTI study objective was to design a power train to provide equivalent performance. There appear to be no technical limitations which would preclude achieving equivalent driving performance.

Question 4. Which fuel cell technology is the better one—hydrogen powered fuel cells or those that use reformers that convert other fuels into hydrogen?

Answer. The potential advantages of using liquid fuels, such as methanol, and reforming them on-board a vehicle to provide hydrogen for a fuel cell are a reduction in the volume and cost for fuel tankage. This must be balanced, however, by the size, weight, capital cost, increased complexity, and maintenance cost of the reformer.

There are also other disadvantages to the on-board reformer option. Additional expense must be incurred to assure that residual carbon monoxide (CO) from the reformer is removed from the fuel gas stream. Even traces of CO will shorten fuel cell catalyst lifetime. The CO removal technology further adds to the weight and cost of the on-board reformer option. The presence of large quantities of carbon dioxide (CO_2) in the reformed gas stream dilutes the hydrogen and results in a decrease in fuel cell performance, requiring a larger, more expensive fuel cell to provide equivalent power. The presence of CO_2 in reformed fuel streams also requires that unused hydrogen be vented or used in heating the reformer. If pure hydrogen is used in the fuel cell, exhaust hydrogen can be recycled to the inlet stream resulting in 100% consumption of the hydrogen. Finally, CO_2 from an on-board reformer cannot be effectively collected for use or sequestering to protect the environment. The use of large centralized reformers to produce pure hydrogen for fueling vehicles would permit such environmental protection while taking advantage of the economies of scale.

In summary, it is our view, and the view of the local transit authority with which we are working on our bus demonstration project, that it is much more desirable to have pure hydrogen on board the vehicle as the fuel.

If I can provide any additional information to assist you, please contact me.

Sincerely yours,

KEITH PRATER,
Vice President, Technology.

ELECTRIC POWER RESEARCH INSTITUTE,
STORAGE AND RENEWABLES DEPARTMENT,
Palo Alto, CA, July 8, 1991.

Hon. WENDELL H. FORD,
Chairman, Subcommittee on Energy Research and Development, U.S. Senate, Committee on Energy and Natural Resources, Washington, DC.

DEAR SENATOR FORD: Enclosed are the answers to the questions regarding S. 1269, that you sent on June 28. EPRI is grateful to have had the opportunity to provide testimony on the "Renewable Hydrogen Energy Research and Development Act of 1991". Your knowledge about the bill and your efforts to obtain and use relevant information are exemplary.

Sincerely,

JAMES R. BIRK,
Director.

[Enclosure.]

Question 1. Are the Department's current hydrogen efforts satisfactory?

Answer. We encourage additional work on production of hydrogen from biomass and on fuel cell powered vehicles.

Question 2. Exactly how do U.S. hydrogen efforts rank in comparison to the efforts of other countries?

Answer. Budgets for hydrogen energy systems, just like budgets for electrical energy systems, are difficult to estimate since they include many separate technologies and activities. For example, budgets for hydrogen energy systems could legitimately include fuel cell and coal gasification technology development. If such technologies are included, U.S. funding is considerably ahead of that of Canada or Germany. If the budget is restricted to the type of work envisioned by S. 1269, our estimate of Canada's annual funding is $5 million and Germany's is $15 million. More exact figures can be obtained for Germany's funding from N. Stump, Project Management for Biology, Ecology, and Energy Research, Kernforschungsanlage Julich GmbH, P.O. Box 1913, D-5170 Julich, Germany and for Canada's funding from Mr. Richard D. Champagne, President, Hydrogen Industry Council, 1801 Avenue McGill College, Bureau 920, Montreal, Quebec, Canada, H3A 2N4.

Question 3. You mentioned in your testimony that if solar and hydrogen are to be integrated, hydrogen should be produced from processes that make hydrogen using the sun directly instead of through electricity. What is the status of these processes in comparison to the more conventional methods?

Answer. At this stage research is directed toward understanding the fundamental science associated with photoelectrochemistry and photosynthesis in an attempt to substantially increase efficiency. Efficiency is now 6% for photoelectrochemical hydrogen and 0.5 to 1.0% for photosynthesis. We need about 15% efficiency for economic viability. It will take 10-20 years to get to laboratory demonstrations achieving this goal.

Question 4. Is it possible to use existing natural gas pipelines to transport hydrogen? What are the problems with transporting hydrogen?

Answer. About 10-15% hydrogen by volume could be transported in natural gas pipelines with minor, if any, adjustment or alteration of end-use appliances. High pressure hydrogen gas pipelines have been in operation for many years in Germany and Texas. The major problem is stress cracking of metallic vessels and pipelines.

Question 5. Can utilities effectively use hydrogen to store excess electricity?

Answer. Using hydrogen to store excess electricity is uneconomical. Capital costs are high in that four separate costly subsystems must be deployed: ac-dc-ac power conditioning systems, electrolyzers, storage of hydrogen, and fuel cells. About half the energy is lost in the storage process. Our projections show that electricity from a hydrogen storage system would cost at least 13¢/kWh from off peak electricity that costs 2¢/kWh using a hydrogen-fueled combined cycle plant to generate the electricity and assuming a 30% capacity factor. Even when inexpensive fuel cells are developed, hydrogen storage systems won't compete with compressed air or pumped hydro storage systems, which are substantially more efficient.

Question 6. Is it more environmentally beneficial to produce and then use hydrogen from natural gas or coal then to use natural gas or coal directly?

Answer. There are two environmental benefits to using hydrogen from fossil fuels: (1) emissions are generated at the point of production of hydrogen and not at the point of use (this is true for electricity also), and (2) once an inexpensive fuel cell is developed, the efficiency of electrical generation from fossil fuels using hydrogen as an intermediary can be increased from 7700 Btu/kWh to 6000 Btu/kWh for natural gas and 9200 Btu/kWh to 7000 Btu/kWh for coal. Improvements in efficiency result

in corresponding improvements of emissions. In addition, since electrical generation with fuel cells does not involve combustion, nitrogen oxide emissions are negligible.

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